Annual Report
Jahresbericht
2016

Leibniz
Ferdinand
Braun
Institut

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At the beginning of 2017, the Ferdinand-Braun-Institut celebrated its 25th anniversary. As a former East-German Academy of Sciences institute, FBH advanced its research areas from then and opened up sustainable topics for the future. In this way, the institute successfully bridges the gap between basic and application-oriented research in photonics and III-V electronics – achieving high international visibility and reputation.

Regarding its photonics research area, FBH has earned itself quite a reputation in high-power diode lasers over the past years. It works especially close with industrial partners in this field, developing novel semiconductor layer designs and optimum resonators for laser bars. It also produces samples in order to verify new findings. Due to the close cooperation with FBH, laser manufacturer Trumpf, for example, was recently able to present the most powerful laser bar of the world, delivering more than 1 kilowatt output power. This is a fourfold increase in output power of CW semiconductor laser bars in less than two and a half years. When it comes to demanding projects conducted in space, the FBH is an equally indispensable partner. With robust and extremely capable diode laser modules, the institute significantly contributed to the world-wide first Bose-Einstein condensate. This is a milestone on the way to exploiting the full potential of quantum technology in the future. The result was achieved in the frame of the Joint Lab Laser Metrology, collectively run by FBH and HU Berlin. Five such collaborations meanwhile exist at FBH: two with TU Berlin, one with HU Berlin, one with Goethe University Frankfurt; and the most recent Joint Lab was started with BTU Cottbus-Senftenberg in 2016. This lab deals with low-noise amplifiers and transistor modeling.

An equally strong demand can be witnessed for the developments originating from FBH's III-V electronics research area, laying the technical foundations for 5G, the next-generation mobile communication standard. This includes devices enhancing the digital proportion of the hardware components, such as efficient digital power amplifiers. They are designed to handle several frequency bands on one chip. Also terahertz power amplifiers gain increasing interest when it comes to the powerful communication of the future. Among other things, applications include security technology for passenger and baggage screening as well as intricate robotics applications.

FBH's success in R&D projects is perfectly reflected by the constantly growing team, which has more than tripled in 25 years – from almost 90 employees in 1992 to currently nearly 300 co-workers. This increase finds its expression in several extension buildings. However, additional space had and still has to be rented on the campus. The FBH works on an increasing number of projects, many of which involve internationally leading results.

This growth path is not finished yet, new developments are coming up. With the "Research Fab Microelectronics Germany", the Federal Ministry for Education and Research has started a cross-institutional initiative for micro- and nanoelectronics in April 2017. The thirteen institutes involved altogether receive more than 350 million Euros funding – more than 34 million Euros of which go to the FBH.

Among others, FBH brings in its expertise in the development of energy-efficient semiconductor components within "Research Fab Microelectronics Germany". It researches novel materials and develops the required devices for applications like electro mobility, alternative energies, and future mobile communications. The institute also develops new devices for the terahertz spectral range including non-destructive testing and quantum technology, which are a prerequisite for data transfer preventing unauthorized eavesdropping and for high-precision measurement equipment. In addition, FBH expands its existing cooperation with the Leibniz institute IHP, in which both institutes combine the high output powers of indium phosphide with the complexity of silicon technology by means of hetero-integrated circuits.

In order to compete internationally, bundling resources and cooperating closely with complementary partners from research and industry becomes more and more important. One example for that is the *Advanced UV for Life* consortium started in 2013. Aim of the 38 partners is to promote technical development, availability, and the use of UV LEDs to a great extent and along the whole value chain.

Taken as a whole, the number of projects yearly realized at FBH has again risen from 2015 to 2016 by almost 7 %, yet with a constant headcount. Our third-party funds also reflect this development. They add up to 14.7 million Euros in 2016 – compared to 12.5 million Euros in 2015 – and are therefore for the first time higher than the basic funding in the amount of 13.2 million Euros. This high share emphasizes the strong international attention and intensive demand from industry. Thus, I like to thank especially our employees at Ferdinand-Braun-Institut who ensure with their know-how and personal commitment that the challenging projects are carried out on the highest level. Our funding partners from the State of Berlin and the Federal Authorities enable us to operate an elaborate and costly infrastructure like FBH's cleanroom, which is an essential prerequisite for state-of-the art research. I therefore like to express my gratitude for their cooperation, which has always been smooth and constructive.

I am looking forward to further exciting developments and the sound cooperation with all of you, and I am also hoping that you enjoy reading through 2016's results and events.

Yours sincerely,

Günther Tränkle

Günther Tränkle

Zu Beginn des Jahres 2017 hat das Ferdinand-Braun-Institut sein 25-jähriges Bestehen gefeiert. Hervorgegangen aus der ehemaligen Akademie der Wissenschaften, entwickelte das FBH seine Forschungsgebiete von damals weiter und hat neue Themenfelder erschlossen. Das Institut schlägt dabei erfolgreich die Brücke zwischen grundlagenorientierter und industrienaher Forschung in der Photonik und III/V-Elektronik – mit hoher internationaler Sichtbarkeit und Reputation.

In seinem Forschungsbereich Photonik hat sich das FBH in den vergangenen Jahren mit Hochleistungs-Diodenlasern einen Namen gemacht – hierbei arbeitet es besonders eng mit Industriepartnern zusammen. Das FBH entwickelt neue Designs der Halbleiterschichten und optimale Resonatoren für Laserbarren. Es stellt auch Muster her, um neue Erkenntnisse zu verifizieren. Dank der engen Kooperation mit dem FBH konnte der Laserhersteller Trumpf erst kürzlich den leistungsstärksten Laserbarren der Welt mit mehr als 1 Kilowatt Ausgangsleistung vorstellen. Dies ist eine Vervierfachung der Leistung bei CW-Halbleiterlaserbarren in nicht einmal zweieinhalb Jahren. Auch bei anspruchsvollen Weltraumprojekten ist das FBH ein unverzichtbarer Partner. Mit robusten und extrem leistungsfähigen Diodenlasermodulen hat es wesentlich zum weltweit ersten Bose-Einstein-Kondensat im Weltraum beigetragen – ein Meilenstein, mit dem sich künftig das volle Potenzial der Quantentechnologie nutzen lassen soll. Dieses Ergebnis wurde im Rahmen des Joint Labs Laser Metrology mit der HU Berlin erzielt. Fünf dieser Kooperationen mit Universitäten gibt es inzwischen am FBH: zwei mit der TU Berlin, eine mit der HU Berlin, eine mit der Goethe-Universität Frankfurt und das jüngste Joint Lab wurde 2016 mit der BTU Cottbus-Senftenberg gestartet. Es beschäftigt sich mit rauscharmen Verstärkern und der Modellierung von Transistoren.

Starke Nachfrage verzeichnen auch die Entwicklungen aus dem FBH-Forschungsbereich III/V-Elektronik, die die technischen Voraussetzungen für 5G schaffen, den Mobilfunkstandard der nächsten Generation. Dazu zählen insbesondere Bauelemente, die den digitalen Anteil der Hardware-Komponenten erhöhen, wie etwa effiziente digitale Leistungsverstärker. Sie sollen künftig mehrere Frequenzbänder auf einem Chip bedienen. Auch Terahertz-Leistungsverstärker rücken in den Fokus, wenn es um die leistungsfähige Kommunikation der Zukunft geht. Sie können unter anderem in der Sicherheitstechnik bei Personen- und Gepäckkontrollen sowie für filigrane Robotik-Anwendungen eingesetzt werden.

Wie erfolgreich das FBH mit seinen F&E-Projekten ist, belegt auch das stetig gewachsene Team, das sich in den 25 Jahren mehr als verdreifacht hat – von knapp 90 Mitarbeiterinnen und Mitarbeitern im Jahr 1992 auf heute fast 300. Dieser Zuwachs hat in mehreren Erweiterungsbauten seinen Niederschlag gefunden, weitere Räume mussten und müssen nach wie vor extern angemietet werden. Das FBH bearbeitet eine stetig steigende Anzahl von Projekten – viele davon resultieren in international führenden Ergebnissen.

Dieser Wachstumspfad ist noch nicht zu Ende, neue Entwicklungen stehen ins Haus. Mit der „Forschungsfabrik Mikroelektronik Deutschland“ hat das Bundesministerium für Bildung und Forschung im April 2017 eine standortübergreifende Initiative für Mikro- und Nanoelektronik ins Leben gerufen. Insgesamt fließen mehr als 350 Millionen Euro an die beteiligten dreizehn Institute – darunter mehr als 34 Millionen Euro an das FBH.

Das FBH bringt im Rahmen der „Forschungsfabrik Mikroelektronik Deutschland“ unter anderem seine Expertise bei der Entwicklung von energieeffizienten Halbleiter-Komponenten ein. Es erforscht neuartige Materialien und entwickelt die notwendigen Bauelemente für Anwendungen wie Elektromobilität, alternative Energien oder die mobile Kommunikation der Zukunft. Es entwickelt zudem neuartige Bauelemente für den Terahertz-Bereich, unter anderem für die zerstörungsfreie Prüfung und die Quantentechnologie, die künftig eine abhörsichere Datenübertragung und hochpräzise Messgeräte ermöglichen soll. Darüber hinaus baut das FBH seine bestehende Kooperation mit dem Leibniz-Institut IHP aus, bei dem beide Institute durch heterointegrierte Schaltungen die hohen Ausgangsleistungen von Indiumphosphid mit der Komplexität der Siliziumtechnologie kombinieren.

Um im internationalen Wettbewerb bestehen zu können, wird es immer wichtiger, die Ressourcen zu bündeln und eng mit komplementären Partnern aus Forschung und Industrie zu kooperieren. Ein Beispiel dafür ist das 2013 gestartete Konsortium *Advanced UV for Life*. Ziel der 38 Partner ist es, die technische Entwicklung, die Verfügbarkeit und den Einsatz von UV-LEDs in breitem Maße und entlang der kompletten Wertschöpfungskette voranzubringen.

Insgesamt ist die Anzahl der am FBH jährlich bearbeiteten Projekte bei gleichem Personalbestand von 2015 auf 2016 erneut um fast 7 % gestiegen. Dies spiegelt sich auch in unseren Drittmitteln wider. Sie liegen mit insgesamt 14,7 Millionen Euro erstmalig über der Grundfinanzierung von 13,2 Millionen Euro – im Vorjahr waren es noch 12,5 Millionen Euro. Dieser hohe Anteil belegt den starken internationalen Zuspruch und die intensive Nachfrage aus der Industrie. Mein Dank gilt daher ganz besonders den Mitarbeiterinnen und Mitarbeitern am Ferdinand-Braun-Institut, die mit ihrem Know-how und persönlichem Einsatz sicherstellen, dass die anspruchsvollen Projekte auf höchstem Niveau durchgeführt werden. Den dafür notwendigen Betrieb des aufwändigen und kostenintensiven Reinraums sichern unsere Zuwendungsgeber des Landes Berlin und des Bundes. Ihnen gilt mein Dank für die stets reibungslose und konstruktive Zusammenarbeit.

Ich freue mich auf weiterhin spannende Entwicklungen und die gute Kooperation mit Ihnen allen. Eine anregende Lektüre der Ergebnisse und Ereignisse aus dem Jahr 2016 wünscht Ihnen, Ihr

Günther Tränkle

Günther Tränkle

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FBH at a glance

The Ferdinand-Braun-Institut, Leibniz-Institut fuer Hoechstfrequenztechnik (FBH) researches electronic and optical components, modules and systems based on compound semiconductors. These devices are key enablers that address the needs of today's society in fields like communications, energy, health, and mobility. Specifically, FBH develops light sources from the visible to the ultra-violet spectral range: high-power diode lasers with excellent beam quality, UV light sources, and hybrid laser modules. Applications range from medical technology, high-precision metrology and sensors to optical communications in space. In the field of microwaves, FBH develops high-efficiency multi-functional power amplifiers and millimeter-wave frontends targeting energy-efficient mobile communications, industrial sensing and imaging, as well as car safety systems. In addition, the institute fabricates laser drivers and compact atmospheric microwave plasma sources operating with economic low-voltage drivers for use in a variety of applications.

The FBH is a competence center for III-V compound semiconductors and has a strong international reputation. FBH competence covers the full range of capabilities, from design through fabrication to device characterization.

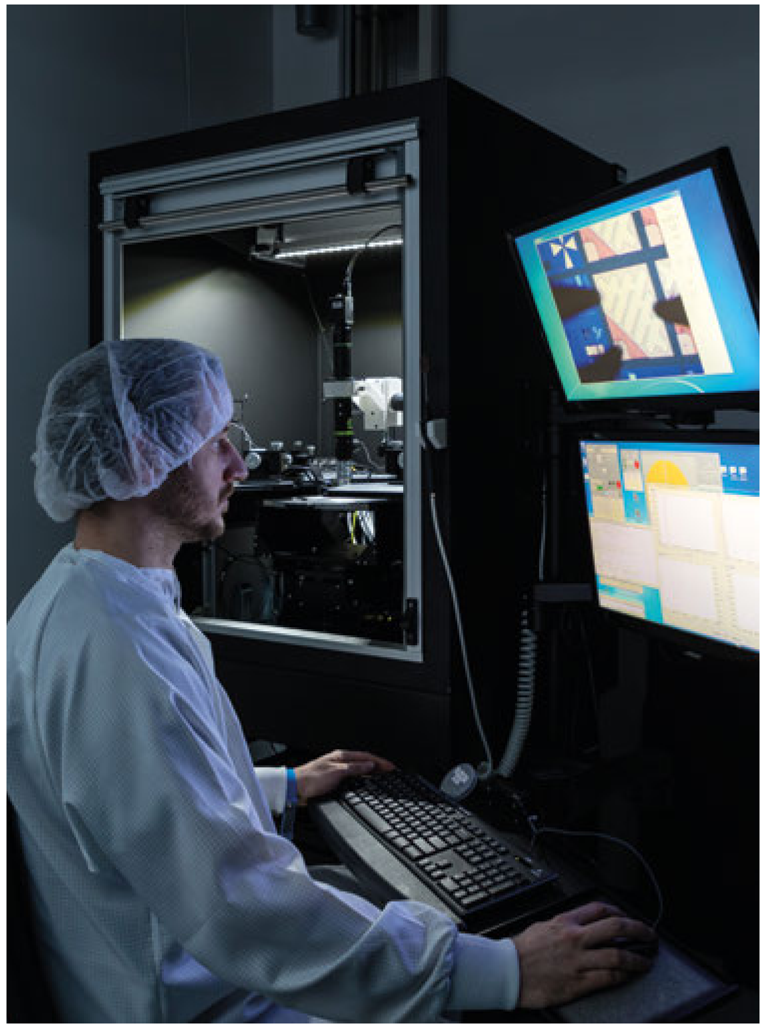
In close cooperation with industry, its research results lead to cutting-edge products. The institute also successfully turns innovative product ideas into spin-off companies. Overall, working in strategic partnerships with industry, FBH ensures Germany's technological excellence in microwave and optoelectronic research.

Das FBH im Profil

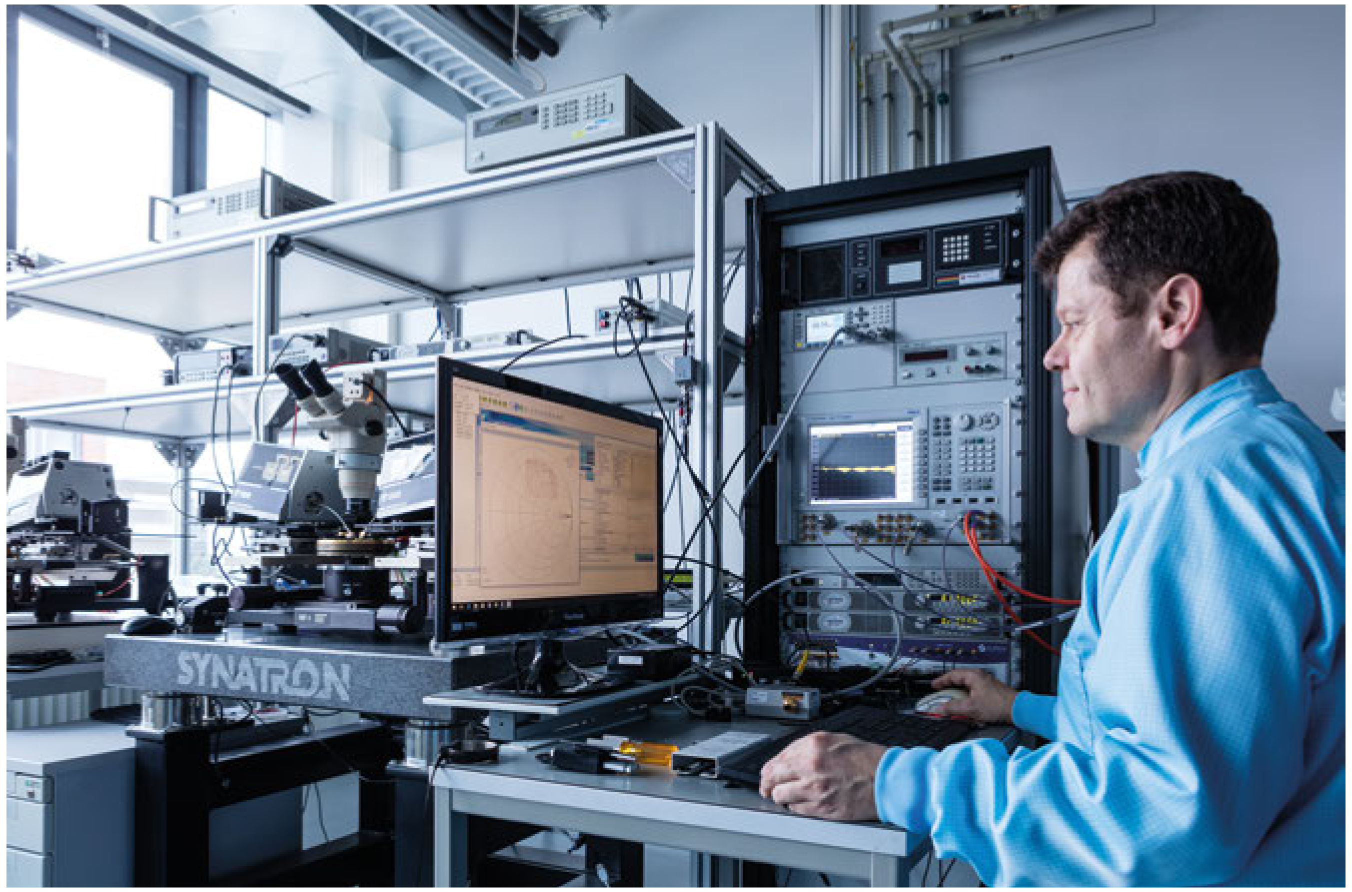
Das Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH) erforscht elektronische und optische Komponenten, Module und Systeme auf der Basis von Verbindungshalbleitern. Diese sind Schlüsselbausteine für Innovationen in den gesellschaftlichen Bedarfsfeldern Kommunikation, Energie, Gesundheit und Mobilität. Leistungsstarke und hochbrillante Diodenlaser, UV-Leuchtdioden und hybride Lasersysteme entwickelt das Institut vom sichtbaren bis zum ultravioletten Spektralbereich. Die Anwendungsfelder reichen von der Medizintechnik, Präzisionsmesstechnik und Sensorik bis hin zur optischen Satellitenkommunikation. In der Mikrowellentechnik realisiert das FBH hocheffiziente, multifunktionale Verstärker und Schaltungen, unter anderem für energieeffiziente Mobilfunksysteme, für industrielle Sensorik und Bildgebung sowie Komponenten zur Erhöhung der Kfz-Fahrsicherheit. Darüber hinaus entwickelt es Lasertreiber sowie kompakte atmosphärische Mikrowellenplasmaquellen mit Niederspannungsversorgung für vielfältige Anwendungen.

Das FBH ist ein international anerkanntes Zentrum für III/V-Verbindungshalbleiter mit allen Kompetenzen: vom Entwurf über die Fertigung bis hin zur Charakterisierung von Bauelementen.

Seine Forschungsergebnisse setzt das FBH in enger Zusammenarbeit mit der Industrie um und transferiert innovative Produktideen und Technologien erfolgreich durch Spin-offs. In strategischen Partnerschaften mit der Industrie sichert es in der Höchstfrequenztechnik die technologische Kompetenz Deutschlands.



Mission statement



… translating ideas into innovation

- We explore cutting-edge technologies for innovative applications in the fields of microwaves and optoelectronics. As a center of competence for III-V compound semiconductors, we are part of a worldwide network and achieve research results advancing the international state-of-the-art.

- We offer complete solutions as a one-stop agency – from design to ready-to-ship modules.

- We work closely cross-linked with the scientific community – including university cooperations (joint labs), strategic networks, and international projects.

- In strategic partnerships with industry, we transfer our research results into cutting-edge products and thus ensure German technological leadership in microwaves and optoelectronics. By means of spin-off companies, we bring innovative product ideas into the market.

- We provide high-value products and services for our customers in the research community and industry which are tailored to fit their individual needs.

- We offer our employees an attractive and family-friendly working environment with interesting tasks and career prospects. To maintain top-level expertise we guide, assist, and encourage young scientists and train our staff.

- We specifically aim at increasing the proportion of female specialists and executive staff in the technical and scientific area and actively assist foreign colleagues with their integration.

Leitbild

... translating ideas into innovation

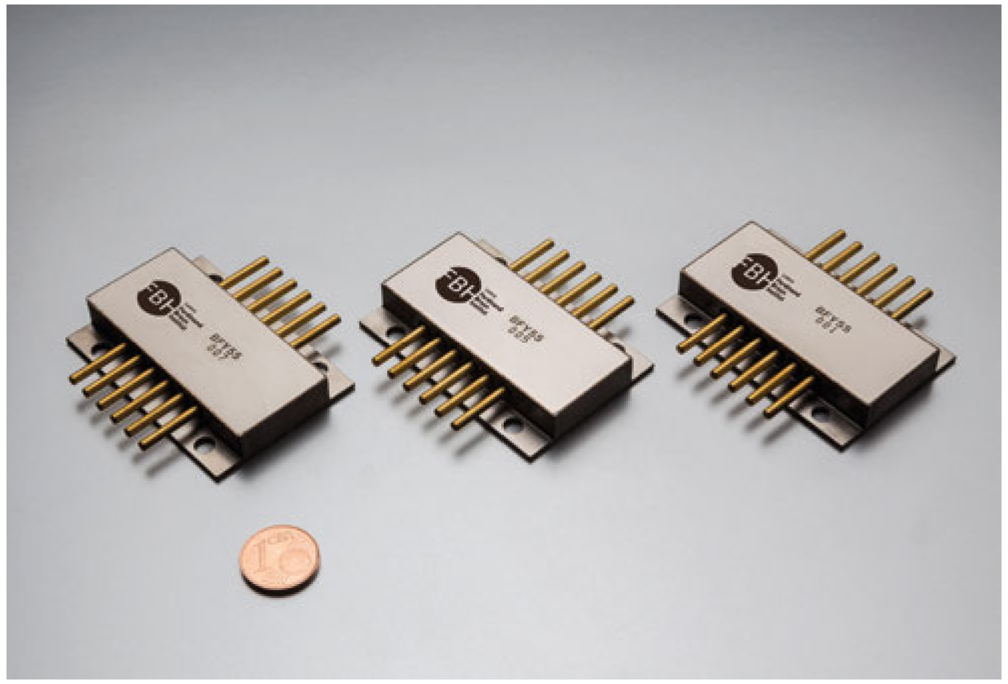
- Wir erforschen Schlüsseltechnologien für innovative Anwendungen in der Mikrowellentechnik und Optoelektronik. Als Kompetenzzentrum für Verbindungshalbleiter arbeiten wir weltweit vernetzt und erzielen Forschungsergebnisse auf internationalem Spitzenniveau.

- Wir bieten Lösungen aus einer Hand: vom Entwurf bis zum lieferfähigen Modul.

- Wir arbeiten eng vernetzt mit der Scientific Community: im Rahmen von Hochschulkooperationen (Joint Labs), strategischen Verbünden und in internationalen Projekten.

- Wir setzen unsere Forschung in strategischen Partnerschaften mit der Industrie in praktische Anwendungen um und sichern so die technologische Kompetenz Deutschlands in der Höchstfrequenztechnik. Innovative Produktideen transferieren wir erfolgreich durch Spin-offs.

- Wir offerieren hochwertige Produkte und Services, die exakt auf die Anforderungen unserer Kunden zugeschnitten sind.



- Wir bieten unseren Mitarbeitern ein stabiles, attraktives und familienfreundliches Arbeitsumfeld mit reizvollen Aufgabenstellungen und Entfaltungsmöglichkeiten. Unsere Zukunft sichern wir durch die gezielte Förderung des wissenschaftlichen Nachwuchses und die Ausbildung technischer Fachkräfte.

- Wir haben es uns zur Aufgabe gemacht, den Anteil weiblicher Fach- und Führungskräfte im technischen und naturwissenschaftlichen Bereich gezielt zu erhöhen sowie ausländische Kolleginnen und Kollegen aktiv bei der Integration zu unterstützen.

Research topics & competencies

The FBH develops high-value products and services for its partners in the research community and industry which are tailored precisely to fit individual needs. The institute offers its international customer base complete solutions and know-how as a one-stop agency – from design to ready-to-ship modules.

Photonics
- high-power diode lasers: broad area & bars
- high-brightness & narrowband diode lasers
- hybrid laser modules (cw & pulsed): from NIR to UV spectral range, e.g. for displays, laser sensors, laser metrology, ...
- nitride laser diodes for the blue & UV spectral range
- short-wave UV LEDs, e.g. for sensors, disinfection, medical & production technology, ...

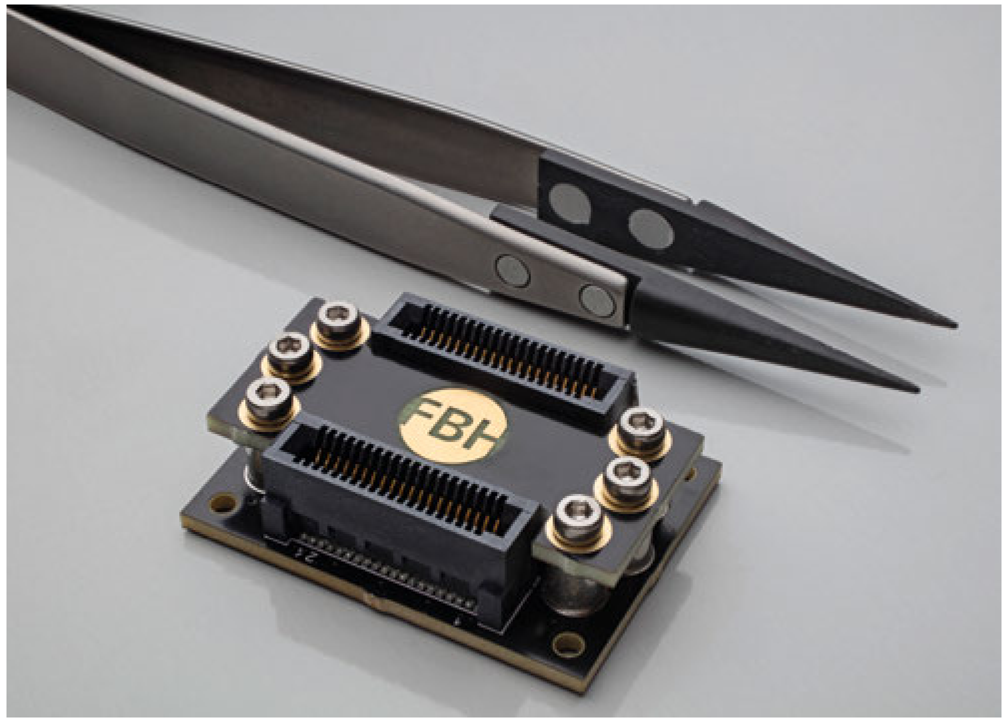
III-V Electronics
- GaN microwave transistors & MMICs
- advanced power amplifier concepts for the wireless infrastructure
- integrated circuits with InP HBTs for the 100...500 GHz frequency range
- fast drivers for laser diodes
- GaN power electronics

III-V Technology
- epitaxy (MOVPE) of GaAs- & GaN-based layer structures for devices
- (Al)GaN HVPE for bulk crystal growth
- in situ control techniques for MOVPE & HVPE
- complete process line 2" - 4" for GaAs, InP, SiC & GaN devices, including laser micro processing
- InP HBT technology for mm-wave & THz applications, hetero-integrated SiGe-BiCMOS/InP-HBT foundry (SciFab) with IHP
- mounting & assembling

Science Management
- technology transfer & marketing
- education & training management

Forschungsthemen & Kompetenzbereiche

Für Partner aus Forschung und Industrie entwickelt das FBH hochwertige Produkte und Services, die exakt auf individuelle Anforderungen zugeschnitten sind. Seinem internationalen Kundenstamm bietet es Know-how und Komplettlösungen aus einer Hand: vom Entwurf bis zum lieferfähigen Modul.



Photonik

- Hochleistungs-Diodenlaser: Breitstreifen & Barren
- Hochbrillante & spektral schmalbandige Diodenlaser
- Hybride Lasermodule (CW & gepulst): NIR bis UV-Spektralbereich, u.a. für Displays, Lasersensorik, Lasermetrologie, ...
- Nitrid-Laserdioden für den blauen & UV-Spektralbereich
- Kurzwellige UV-Leuchtdioden, u.a. für Sensorik, Desinfektion, Medizin- und Produktionstechnik, ...

III/V-Elektronik

- GaN-Mikrowellentransistoren & -MMICs
- Neue Leistungsverstärkerkonzepte für die drahtlose Infrastruktur
- Integrierte Schaltungen mit InP-HBTs für den Frequenzbereich 100...500 GHz
- Schnelle Treiber für Laserdioden
- GaN-Leistungselektronik

III/V-Technologie

- Epitaxie (MOVPE) von GaAs- & GaN-basierten Schichtstrukturen für Bauelemente
- (Al)GaN-HVPE für Volumenkristalle
- In-situ Kontrolltechniken bei MOVPE & HVPE
- Komplette Prozesslinie 2" - 4" für GaAs-, InP-, SiC- & GaN-Bauelemente inklusive Lasermikrostrukturierung
- InP-HBT-Technologie für Millimeterwellen- & THz-Anwendungen, heterointegrierter SiGe-BiCMOS-/InP-HBT-Foundryprozess (SciFab) mit dem IHP
- Aufbau- & Verbindungstechnik

Wissenschaftsmanagement

- Technologietransfer & Marketing
- Bildungsmanagement

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III-V Technology III/V-Technologie	Prof. Dr. rer. nat. Markus Weyers Phone +49.30.6392-2670 markus.weyers@fbh-berlin.de

Forschungsverbund Berlin e.V.

The Forschungsverbund Berlin e.V. represents eight research institutes in Berlin – one of them being the Ferdinand-Braun-Institut. The institutes are active in the fields of natural sciences, life sciences, and environmental sciences. They pursue common interests within the framework of a single legal entity while maintaining their scientific autonomy. As research institutes of national scientific importance, they are jointly funded by the German federal and state governments. The institutes share an administrative infrastructure (Common Administration, Head Dr. Manuela Urban) and are member of the Leibniz Association.

The institute directors and other senior scientists hold chairs at the Berlin/Brandenburg universities, thus ensuring close contact with teaching and research in higher education.

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FVB Forschungsverbund
Berlin e.V.

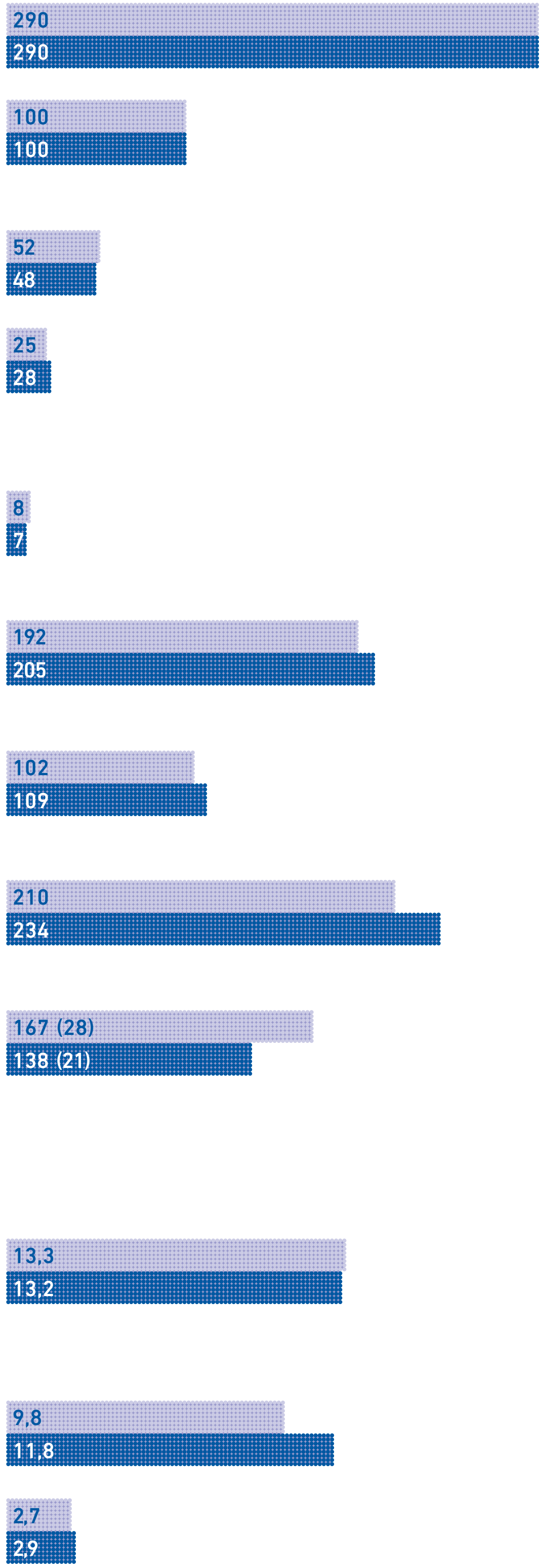
Der Forschungsverbund Berlin e.V., zu dem auch das Ferdinand-Braun-Institut gehört, ist Träger von acht natur-, lebens- und umweltwissenschaftlichen Forschungsinstituten in Berlin. Alle Institute sind wissenschaftlich eigenständig, nehmen aber im Rahmen einer einheitlichen Rechtspersönlichkeit gemeinsame Interessen wahr. Als Forschungseinrichtungen von überregionaler Bedeutung und gesamtstaatlichem wissenschaftspolitischen Interesse werden die Institute im Rahmen der gemeinsamen Forschungsförderung von Bund und Ländern finanziert. Sie verfügen über eine gemeinsame administrative Infrastruktur (Verbundverwaltung, Geschäftsführerin Dr. Manuela Urban) und sind Mitglied der Leibniz-Gemeinschaft.

Die Direktorinnen und Direktoren der Institute und weitere leitende Wissenschaftlerinnen und Wissenschaftler haben Professuren an den Universitäten in Berlin/Brandenburg inne und sichern so die enge Verbindung zu Lehre und Forschung in den Hochschulen.

The institute in figures
Das Institut in Zahlen

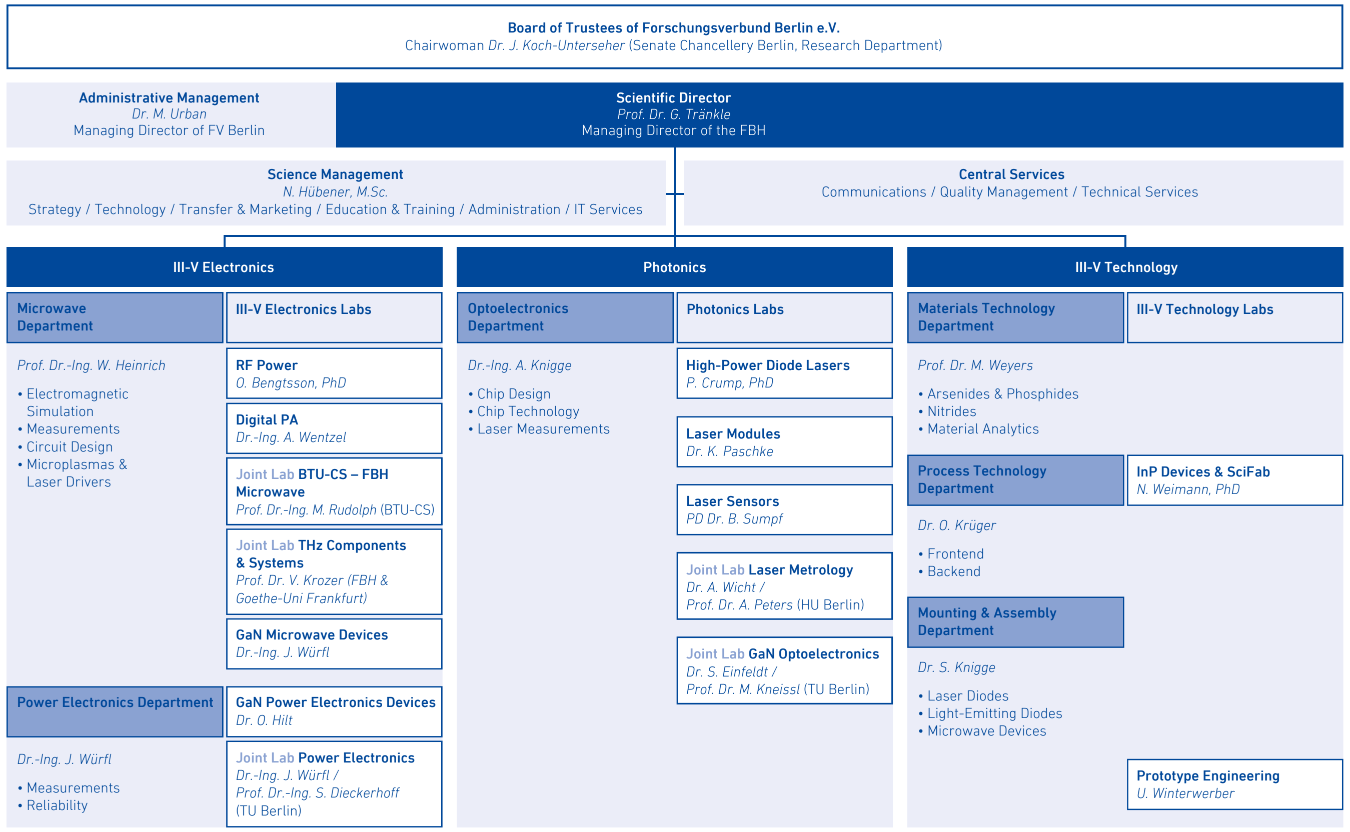
Founded 1992
Gegründet 1992

	2015	2016
Staff **Team**	290	290
Scientists Wissenschaftlerinnen & Wissenschaftler	100	100
PhD candidates Promovierende	52	48
Student assistants & bachelor/master students Studentische Hilfskräfte & Bachelor-/Masterstudierende	25	28
Trainees Auszubildende	8	7
Projects **Laufende Projekte**	192	205
Publications (peer reviewed) **Publikationen (referiert)**	102	109
Patents **Patente**	210	234
Talks (invited) **Vorträge (eingeladene)**	167 (28)	138 (21)
Budget (in million Euros) **Umsatz (Mio. Euro)**		
Basic funding: State of Berlin and Federal Government Grundfinanzierung durch das Land Berlin und den Bund	13,3	13,2
Public project funding Öffentliche Drittmittel	9,8	11,8
Industrial contracts Industrielle Auftragsforschung	2,7	2,9



▨ 2015
■ 2016

Organizational chart
Organigramm



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Administrative Management
Dr. M. Urban
Managing Director of FV Berlin

Scientific Director
Prof. Dr. G. Tränkle
Managing Director of the FBH

Science Management
N. Hübener, M.Sc.
Strategy / Technology / Transfer & Marketing / Education & Training / Administration / IT Services

Central Services
Communications / Quality Management / Technical Services

III-V Electronics

Microwave Department
Prof. Dr.-Ing. W. Heinrich
- Electromagnetic Simulation
- Measurements
- Circuit Design
- Microplasmas & Laser Drivers

III-V Electronics Labs

RF Power
O. Bengtsson, PhD

Digital PA
Dr.-Ing. A. Wentzel

Joint Lab **BTU-CS – FBH Microwave**
Prof. Dr.-Ing. M. Rudolph (BTU-CS)

Joint Lab **THz Components & Systems**
Prof. Dr. V. Krozer (FBH & Goethe-Uni Frankfurt)

GaN Microwave Devices
Dr.-Ing. J. Würfl

Power Electronics Department
Dr.-Ing. J. Würfl
- Measurements
- Reliability

GaN Power Electronics Devices
Dr. O. Hilt

Joint Lab **Power Electronics**
Dr.-Ing. J. Würfl /
Prof. Dr.-Ing. S. Dieckerhoff
(TU Berlin)

Photonics

Optoelectronics Department
Dr.-Ing. A. Knigge
- Chip Design
- Chip Technology
- Laser Measurements

Photonics Labs

High-Power Diode Lasers
P. Crump, PhD

Laser Modules
Dr. K. Paschke

Laser Sensors
PD Dr. B. Sumpf

Joint Lab **Laser Metrology**
Dr. A. Wicht /
Prof. Dr. A. Peters (HU Berlin)

Joint Lab **GaN Optoelectronics**
Dr. S. Einfeldt /
Prof. Dr. M. Kneissl (TU Berlin)

III-V Technology

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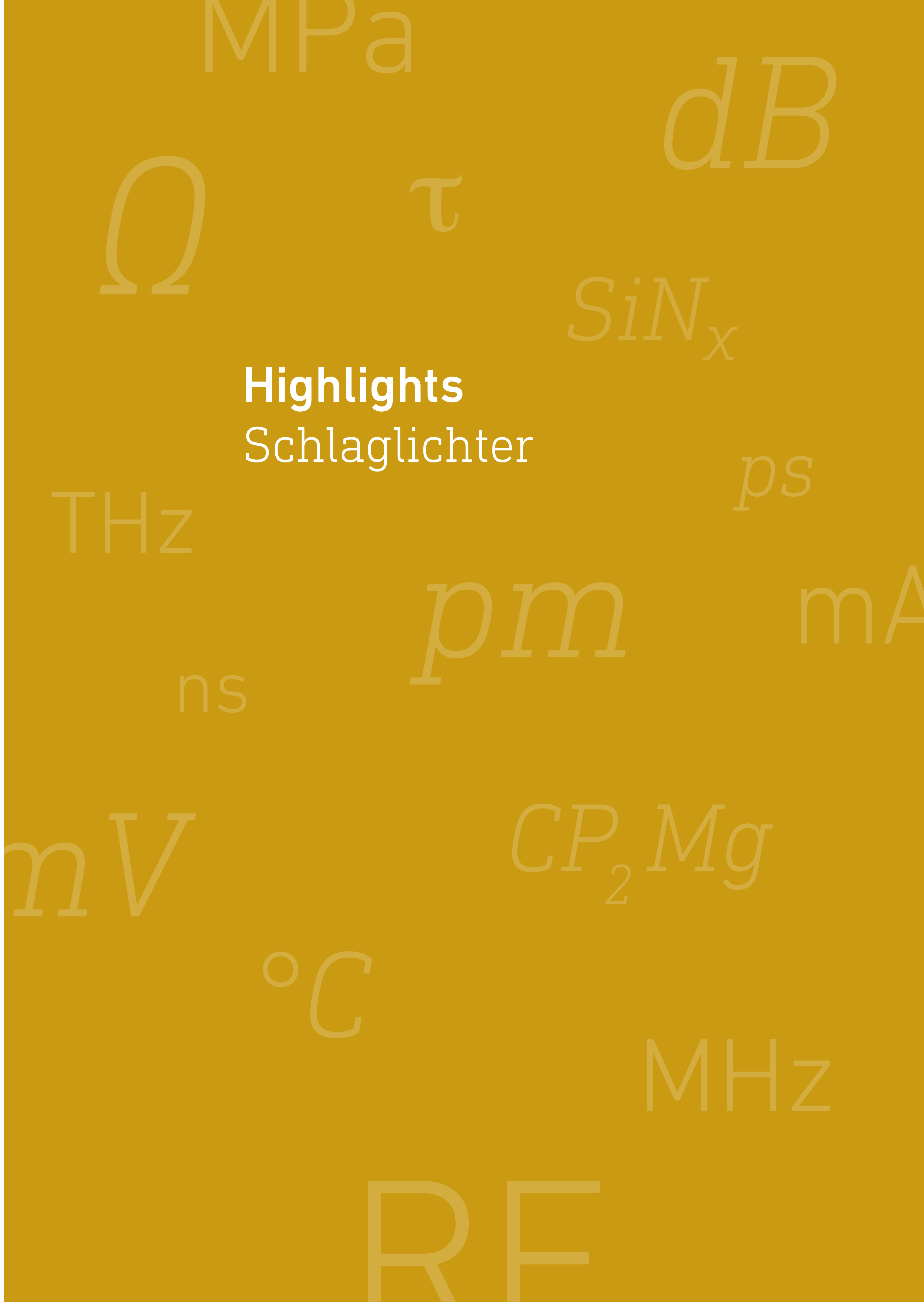
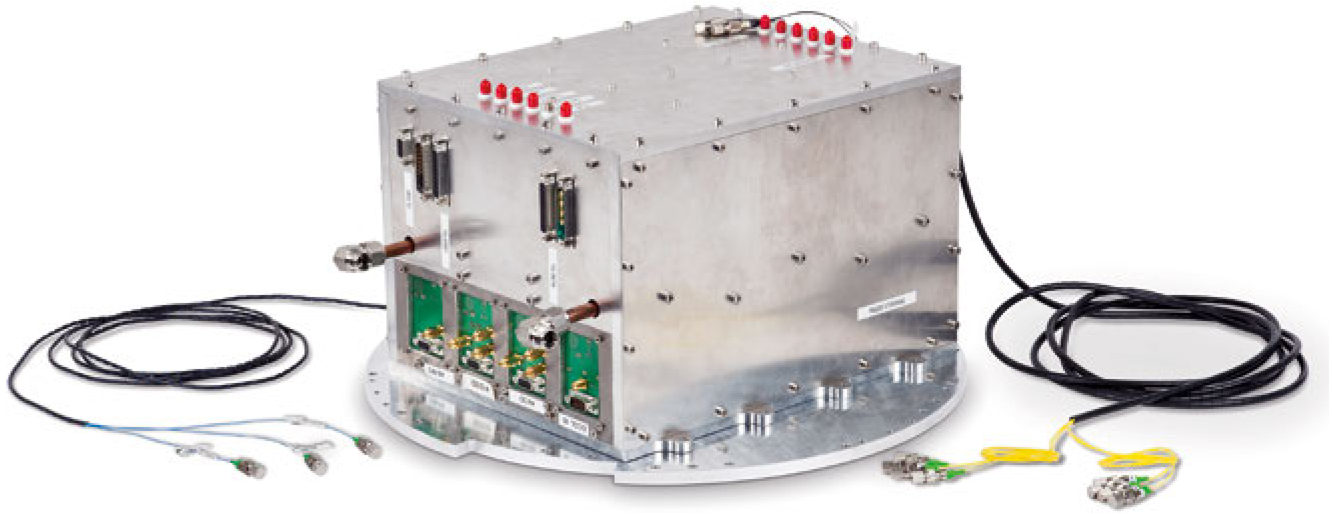


Highlights
Schlaglichter

First Bose-Einstein condensate in space – created by powerful laser modules from FBH

In January 2017, on board a sounding rocket launched as part of the *MAIUS* mission, a Bose-Einstein condensate (BEC) was created for the first time in space. A BEC is a state of matter that allows ultra-precise measurements. This was proof that quantum-optical sensors can be used even in harsh environments like space. It also means it is now possible to exploit the full potential of this quantum technology to find answers to the fundamental questions of physics. Such experiments are furthermore innovation-drivers for a wide range of applications from GPS-free navigation to space-borne geodesy, the measurement and description of the earth.



***MAIUS* laser system used to successfully create a Bose-Einstein condensate for the first time in space. It is about as big as a shoe box with a mass of 27 kg.**
MAIUS-Lasersystem, mit dem im Weltraum erstmalig ein Bose-Einstein-Kondensat erzeugt wurde. Es ist in etwa so groß wie ein Schuhkarton und 27 kg schwer.

Combined expertise for *MAIUS*

The *MAIUS* experiments are testimony to the successful collaboration between the Ferdinand-Braun-Institut and Humboldt-Universität zu Berlin (HU) in their Joint Lab Laser Metrology. It is not the first time the two institutions have employed laser technology in space. In April 2015 and in January 2016, technological components of the *MAIUS* mission were successfully tested on board two sounding rockets in the experiments *FOKUS* and *KALEXUS*. Such tests are bringing the joint project *QUANTUS*, Quantengase unter Schwerelosigkeit (quantum gases in microgravity), funded by the German Aerospace Center (DLR), closer to its final goal of using ultra-cold atoms as ultra-precise quantum sensors in microgravity. *QUANTUS* has been the umbrella project for many experiments since 2004.

In *MAIUS*, directed by the Optical Metrology workgroup of HU, a compact and stable diode laser system was developed for performing laser cooling and atomic interferometry with ultra-cold rubidium atoms on a sounding rocket. The laser system for operating the main experiment consists of four diode laser modules built by FBH as hybrid-integrated laser modules. The master lasers each comprise a monolithic distributed-feedback (DFB) laser frequency-stabilized to the frequency of an optical transition in rubidium. These lasers produce spectrally pure and highly stable (~ 1 MHz linewidth) optical radiation of 780 nanometer wavelength at low power (a few tens of milliwatts). Three hybrid integrated master oscillator power amplifiers calibrated to the master lasers are responsible for the laser cooling of the atoms and for the interferometry. Using a tapered amplifier with a ridge waveguide input section, they boost the beam from a DFB laser to powers beyond 1 watt without loss of spectral stability. The laser light is distributed and transmitted to the experimental chamber through fiber optic components. Acusto-optical modulators are used in a free beam setup for fast switching of the light.

A glimpse into the future – quantum optical technologies

Quantum technologies exploit specific characteristics and degrees of freedom of quantum mechanics, such as discrete energy levels, superimposed states, quantum entanglement, and the tunneling effect. Thus, the quantum mechanical nature of atoms or light particles – photons – can be used for diverse applications in very different fields. These could be quantum optical sensors, for example, or intrinsically tap-proof communication systems. If two communicating parties exchange random secret keys, the laws of quantum mechanics ensure that any attempt at eavesdropping is detected, and a compromised key can be immediately discarded. Aside from quantum communication, other fields of application include quantum computing, quantum simulation, and quantum-assisted imaging and spectroscopy.

All quantum optical applications require beam sources and optical components with very specific properties for the respective application. Primary concerns in the development of these technologies are electro-optical performance, compactness, robustness, and scalability of the manufacturing process. Only when true advancements are made in these areas will it be possible to exploit the full potential of quantum optical technology, with genuine social and economic relevance. FBH is involved at every level of this high-performance technology, with activities ranging from the development of special laser chips and hybrid microintegration to support in the application. In particular, it will continue expanding its cooperation with local partner Humboldt-Universität zu Berlin in the scope of the Joint Lab Laser Metrology.

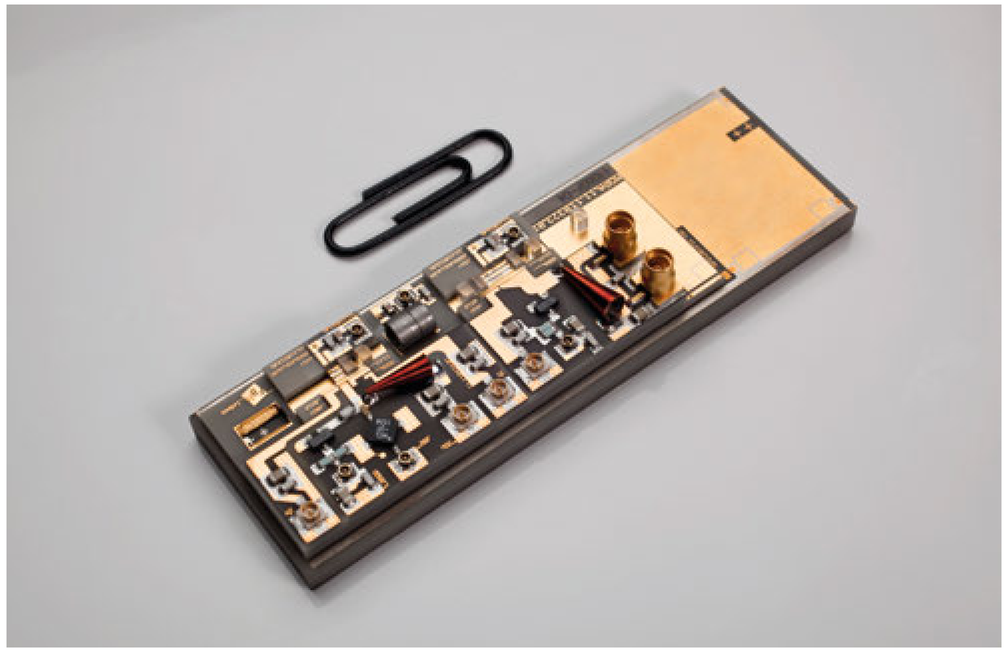
Erstes Bose-Einstein-Kondensat im Weltraum – FBH mit leistungsfähigen Lasermodulen beteiligt

Im Januar 2017 wurde im Rahmen der *MAIUS*-Mission an Bord einer Höhenforschungsrakete erstmals ein Bose-Einstein-Kondensat im Weltraum erzeugt – ein Materiezustand, der hochgenaue Messungen ermöglicht. Damit gelang der Nachweis, dass quantenoptische Sensoren auch in rauen Umgebungen wie dem Weltraum eingesetzt werden können. Künftig soll sich so das volle Potenzial der Quantentechnologie nutzen lassen, um grundlegende physikalische Fragestellungen beantworten zu können. Zugleich sind derartige Experimente Innovationstreiber für ein breites Spektrum an Anwendungen, von der GPS-freien Navigation bis hin zur weltraumgestützten Geodäsie, der Vermessung und Beschreibung der Erdform.

Gebündelte Kompetenz für *MAIUS*

Die *MAIUS*-Experimente belegen die erfolgreiche Zusammenarbeit des Ferdinand-Braun-Instituts und der Humboldt-Universität zu Berlin (HU) in ihrem Joint Lab Laser Metrology. Für beide Einrichtungen ist dies nicht der erste Einsatz ihrer Lasertechnologie im Weltraum. Bereits im April 2015 und Januar 2016 konnten Technologiebausteine der *MAIUS*-Mission an Bord zweier Höhenforschungsraketen in den Experimenten *FOKUS* und *KALEXUS* erfolgreich getestet werden. Derartige Tests bringen das vom Deutschen Zentrum für Luft- und Raumfahrt (DLR) geförderte Verbundprojekt *QUANTUS* (Quantengase unter Schwerelosigkeit) seinem Ziel näher: ultrakalte Atome als ultrapräzise Quantensensoren in Mikrogravität einzusetzen. Verschiedene Experimente beschäftigen sich damit seit 2004 unter dem Dach von QUANTUS.

In *MAIUS* wurde unter der Leitung der Arbeitsgruppe Optische Metrologie der HU ein kompaktes und stabiles Diodenlasersystem für die Laserkühlung und Atominterferometrie mit ultra-kalten Rubidium-Atomen auf einer Höhenforschungsrakete entwickelt. Das Lasersystem für den Betrieb des Hauptexperimentes setzt sich aus vier Diodenlasermodulen zusammen, die das FBH als hybrid-integrierte Lasermodule realisiert hat. Die Master-Laser bestehen jeweils aus einem monolithischen Distributed-Feedback (DFB)-Laser, dessen Frequenz auf die eines optischen Übergangs in Rubidium stabilisiert ist. Sie erzeugen spektral reine und hochstabile (~ 1 MHz Linienbreite) optische Strahlung geringer Leistung (einige 10 mW) bei 780 Nanometern Wellenlänge. Drei auf diesen Master-Laser referenzierte, hybrid-integrierte Master-Oscillator-Power-Amplifier sind für die Laserkühlung der Atome und für die Interferometrie zuständig. Bei ihnen wird die Strahlung eines DFB-Lasers ohne Verlust der spektralen Stabilität mit einem Trapezverstärker mit einer Rippenwellenleiter-Eingangssektion bis zu Leistungen jenseits von 1 Watt nachverstärkt. Das Laserlicht wird mittels faseroptischer Bauelemente aufbereitet und an die Experimentierkammer weitergeleitet, zum schnellen Schalten des Lichts werden akusto-optische Modulatoren in einem Freistrahlaufbau genutzt.



Hybrid-integrated master oscillator power amplifier laser module for rubidium precision spectroscopy in space developed by the FBH.
Hybrid integriertes Master-Oscillator-Power-Amplifier-Laser-modul aus dem FBH für die Rubidium-Präzisionsspektroskopie im Weltraum.

Blick in die Zukunft – quantenoptische Technologien

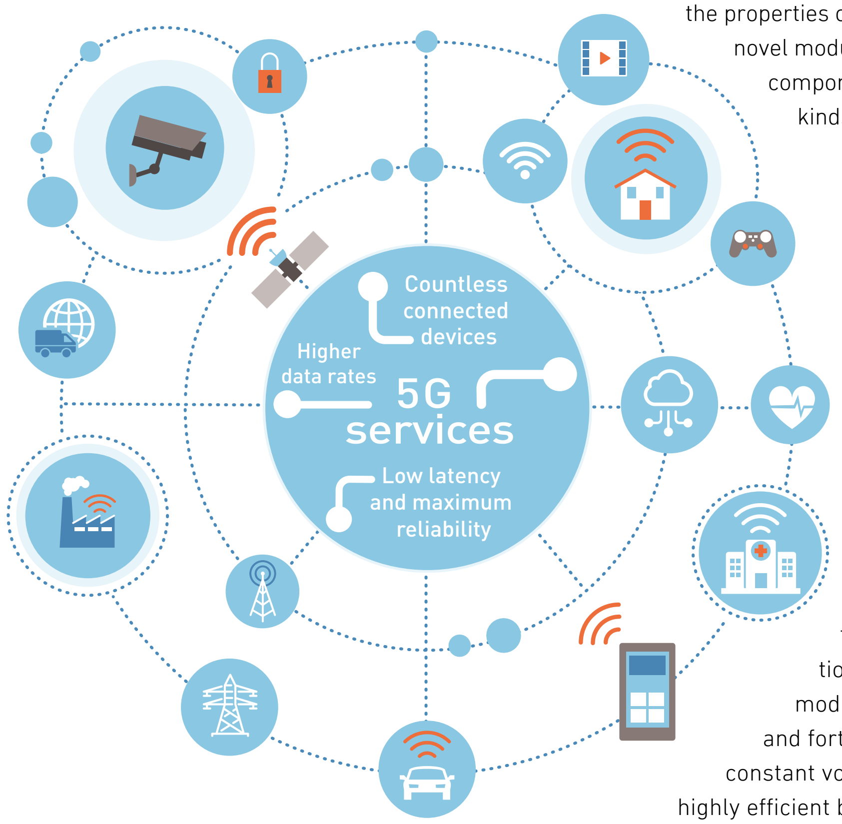
Die Quantentechnologie nutzt spezifische Eigenschaften und Freiheitsgrade der Quantenmechanik. Dazu zählen diskrete Energieniveaus, Zustandsüberlagerung, Quantenverschränkung oder der Tunneleffekt. Die quantenmechanische Natur von Atomen und Lichtteilchen, den Photonen, kann damit für vielfältige Anwendungen in sehr unterschiedlichen Bereichen genutzt werden. Zu diesen gehört neben quantenoptischen Sensoren beispielsweise eine per se abhörsichere Kommunikation. Hier stellen die Gesetze der Quantenmechanik sicher, dass Schlüssel zwischen zwei Partnern so ausgetauscht werden, dass eine Abhöraktion erkannt und ein kompromittierter Schlüssel verworfen werden kann. Weitere Anwendungsfelder sind das Quanten-Computing, die Quanten-Simulation, die quantenunterstützte Bildgebung und Spektroskopie sowie die Quanten-Kommunikation.

Für alle quantenoptischen Anwendungen werden Strahlungsquellen und optische Aufbauten mit ganz besonderen, von der Anwendung festgelegten Eigenschaften benötigt. Neben der elektro-optischen Leistungsfähigkeit stehen auch die Kompaktheit und Robustheit, sowie die Skalierbarkeit des Fertigungsprozesses bei der Technologieentwicklung im Vordergrund. Nur mit umfassenden Entwicklungen in diesen Bereichen können quantenoptische Technologien ihr Potenzial voll ausschöpfen und die entsprechende gesellschaftliche und ökonomische Relevanz erreichen. Das FBH unterstützt diese leistungsfähige Technologie mit seinen Arbeiten von der Entwicklung spezieller Laserchips, über die hybride Mikrointegration bis zur Begleitung in die Anwendung. Dazu soll in Zukunft die Zusammenarbeit insbesondere mit dem lokalen Partner Humboldt-Universität zu Berlin im Rahmen des Joint Labs weiter ausgebaut werden.

Components for the future mobile telecommunications standard 5G

As successor to LTE, the next mobile telecommunications standard 5G promises a quantum leap in wireless communication, by which everyone will be connected to everything. 5G will boast very high data rates with ultra-reliability and extremely low latency. These functionalities are prerequisites not only for interactive, high-resolution entertainment applications, but also for driverless cars, intelligent buildings, and networked factories. It will even allow surgeons to perform remote operations on the other side of the world by controlling robots in real time. Optimistic estimates state that the first systems will already be available in 2020.

The task at present is to develop the technologies needed to achieve these ambitious goals. Challenges on the hardware side include overhauling the device designs to make them operate on new frequency bands – below six gigahertz and in the millimeter wavelength range. Plus, it will require a tight-knit wireless network, which can only be established after there has been a massive expansion of base stations and mobile communication nodes. Also needed are more flexible air interfaces and novel multi-antenna systems (MIMO technology), by which the spatial parallelism of connections can be increased. At the same time, this higher performance of the technical infrastructure must not come at the cost of higher energy consumption; the goal is even to lower the overall power consumption of mobile base stations.

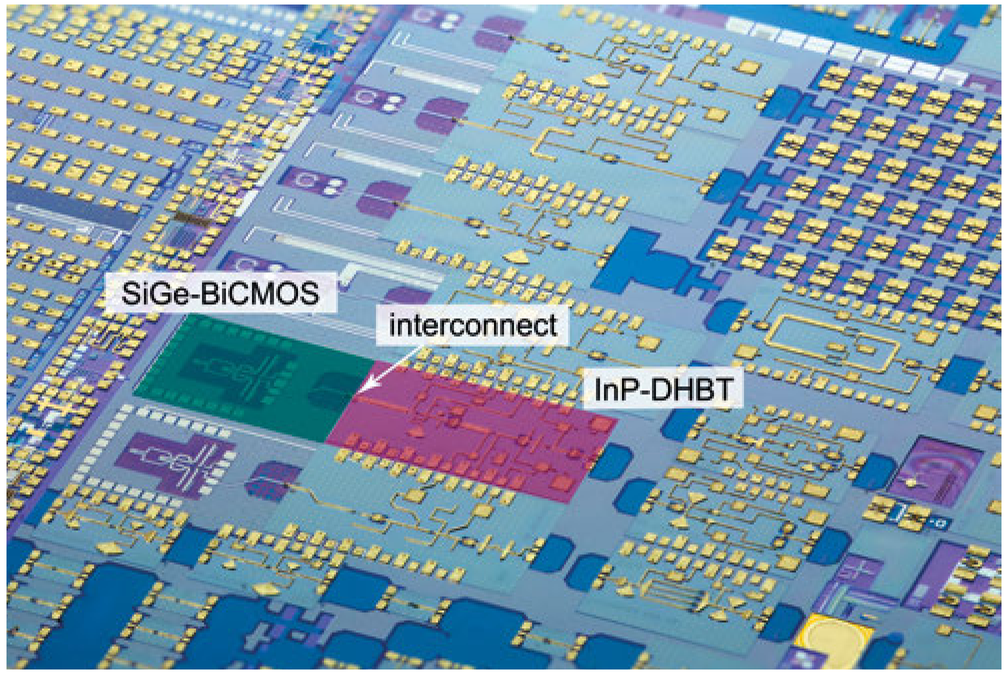


Increased digitalization

In preparing the technical infrastructure for 5G, the hardware components will have to be made more efficient and more flexible. This can be achieved, among other things, by increasing the degree of digitalization. Currently, focus is on power amplifiers because they dominate the efficiency, and thus the operating costs, of the entire system. Up to now, the efficiency of power amplifiers has always been relatively low, and a given amplifier can only operate in one frequency band. Accordingly, multiple separate modules have always been required to accommodate different communication standards and frequencies. FBH has therefore been working for several years on developing new digital amplifier architectures offering efficient power management, utmost flexibility, and broadband operation. The long-term goal is a fully digital transmitter in which one chip serves all frequency bands. Complementary to this, FBH is researching powerful modulation and encoding methods, which largely determine the properties of digital amplifiers. FBH has already developed a novel modulator that can be built using conventional digital components. It also allows signals to be generated by all kinds of modulation methods.

FBH digital power amplifiers already achieve competitive values in terms of overall efficiency and linearity compared to established analog amplifier concepts such as Doherty. One power amplifier recently developed at FBH offers high overall efficiency of greater than 40 % at 10 dB PAPR bandwidth in the range of around 1 GHz. PAPR refers to the ratio of peak power to mean power of a signal.

Another method for digitalizing power amplifiers is Discrete Envelope Tracking (ET). Modulating the supply voltage of the output amplifier ensures high power efficiency despite the strongly fluctuating instantaneous power of modern broadband modulation methods. In Discrete Envelope Tracking, this modulation is done by switching the voltage back and forth only between a number of specific (discrete) constant voltages. This digitalized version of ET yields highly efficient broadband solutions. New international records were recently achieved at FBH, namely a modulation bandwidth of 160 MHz in a 60 W amplifier at 1.8 GHz. This ET concept can also be relatively easily converted for millimeter-wavelength amplifiers, as is crucial for 5G base stations.



Combines the advantages of two technologies on chip level: InP-DHBT circuit from the FBH on IHP's SiGe-BiCMOS wafer.
Kombiniert die Vorteile zweier Technologien auf Chipebene: InP-DHBT-Schaltung aus dem FBH auf SiGe-BiCMOS-Wafer des IHP.

Pushing the frequency boundaries – with terahertz power amplifiers

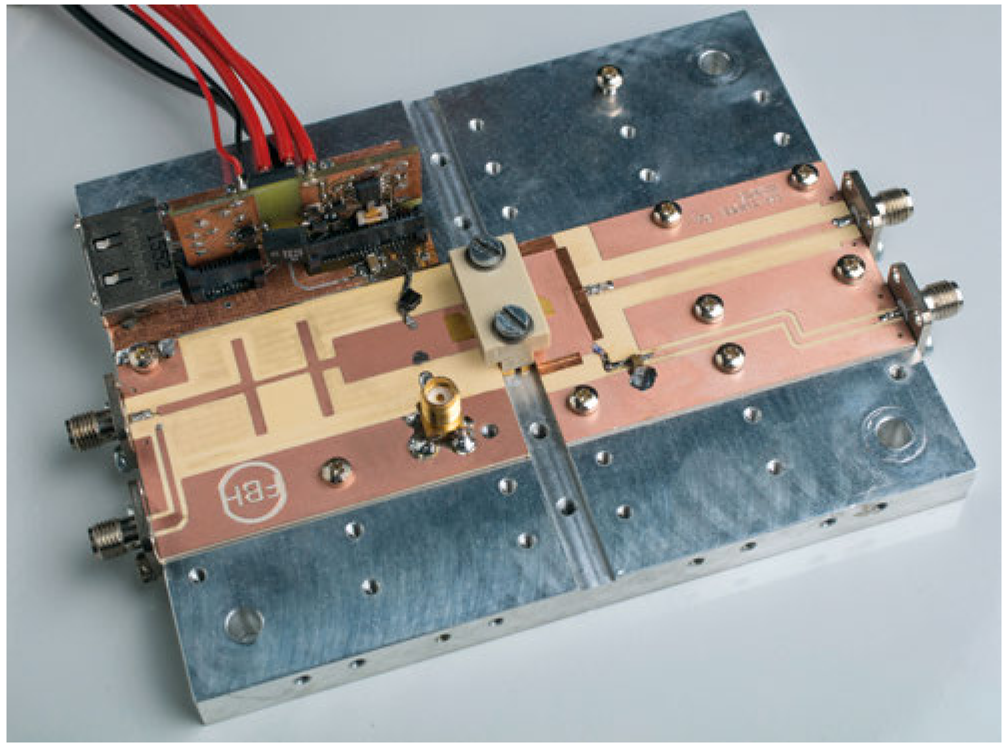
When it comes to the future of high performance communication, frequencies in the sub-terahertz range are gaining increasing attention. Wireless transmission routes are needed in the frequency band between 100 and 500 GHz in order to overcome the exponentially growing volume of short-range data traffic. Other applications in this frequency band include materials testing, security technology for passenger and baggage screening, and high-resolution radar technology for intricate robotics applications. All of these system applications require electronic circuits that can deliver high output power in the sub-terahertz range – and they cannot be built using conventional semiconductor technology. Instead, the semiconductor material indium phosphide (InP) must be used. A process line for integrated circuits featuring InP transistors is being built at FBH in the scope of the BMBF initiative *Research Fab Microelectronics Germany (FMD)*, launched in April this year. At this research factory, InP circuit wafers can be produced to industrial quality standards using latest-generation equipment.

The process line at FBH also allows InP circuits, developed together with the Leibniz institute IHP in the scope of FMD, to be integrated onto silicon wafers. Thus the high output powers of InP can be combined with the complexity of silicon technology. This way, millimeter-wave and sub-terahertz modules can be created on a single chip, which is paramount for portable and cost-effective system applications.

Novel transistors successful in the Leibniz Association's bidding competition

Another project examining application scenarios of future mobile telecommunications systems is *AlPower* (AlN electronics for a new generation of high-power devices), for which FBH successfully bid in the Leibniz Competition at the end of 2016. High powers, voltages and speeds can only be combined to achieve greatest efficiency if novel power and switching transistors are introduced. Aluminum nitride (AlN)-based transistors should meet the requirements and ensure especially efficient energy conversion in diverse applications. These include mobile communications, autonomous driving, a reliable IT energy supply, and industrial drive technology.

These applications require new, especially efficient transmitter solutions that can still deliver high voltages in the 50 volt range at frequencies beyond 20 GHz – a frequency and voltage combination that is unattainable by conventional gallium nitride-based transistors. The novel HFETs (heterostructure field effect transistors) based on aluminum nitride ought to remove this limitation. Using an AlN/GaN/AlN semiconductor structure with an extremely thin AlN barrier should keep the electrons confined to the transistor channel even in very high



Discrete Envelope Tracking system for efficient broadband communication.
Discrete-Envelope-Tracking-System für die effiziente und breitbandige Kommunikation.

electric fields. This, in turn, should make it possible to build efficient high-power amplifiers running at > 20 GHz, as well as efficient 1200 volt switching power converters operating at unprecedented speeds and power densities. Furthermore, the project will demonstrate a 30 GHz prototype of 10 watt power output for serving the future mobile telecommunications frequency bands. Finally, an especially compact 400 volt matrix converter will be developed for motor regulation. For these developments in AlPower, FBH will be receiving 1.06 million Euros in funding over the next three years.

Komponenten für den Mobilfunkstandard der Zukunft 5G

Nach LTE verspricht der nächste Mobilfunkstandard 5G einen Quantensprung für die drahtlose Kommunikation, bei der alle mit allem vernetzt sein werden. 5G punktet dabei mit höchsten Datenraten sowie extrem niedrigen Latenzzeiten bei maximaler Zuverlässigkeit. Diese Funktionalitäten sind die Voraussetzung für interaktive, hochaufgelöste Entertainment-anwendungen ebenso wie für selbstfahrende Autos, intelligente Häuser und vernetzte Fabriken. Sogar Operationen könnten in Echtzeit über einen Roboter durchgeführt werden, der von einem Arzt am anderen Ende der Welt gesteuert wird. Erste Systeme sollen dem ambitionierten Zeitplan zufolge bereits ab 2020 zur Verfügung stehen.

Dafür gilt es nun die technischen Voraussetzungen zu schaffen, mit der sich die anspruchsvollen Zielstellungen erfüllen lassen. Zu den Herausforderungen auf Hardware-Seite zählen, dass die Geräte neue Frequenzbänder bedienen müssen – im Bereich unter sechs Gigahertz ebenso wie im Millimeterwellenbereich. Hinzu kommt ein engmaschiges Funknetz, was mit einem massiven Ausbau von Basisstationen beziehungsweise Mobilfunkknoten verbunden ist. Benötigt werden auch flexiblere Luftschnittstellen und neuartige Mehr-Antennen-Systeme (MIMO-Technologie), mit denen sich die räumliche Parallelität von Verbindungen erhöhen lässt. Zugleich soll die höhere Leistungsfähigkeit der technologischen Infrastruktur nicht etwa durch einen höheren Energieverbrauch erkauft werden, erwünscht ist sogar, dass der Energieverbrauch von Mobilfunkbasisstationen sinkt.

Mehr Digitalisierung

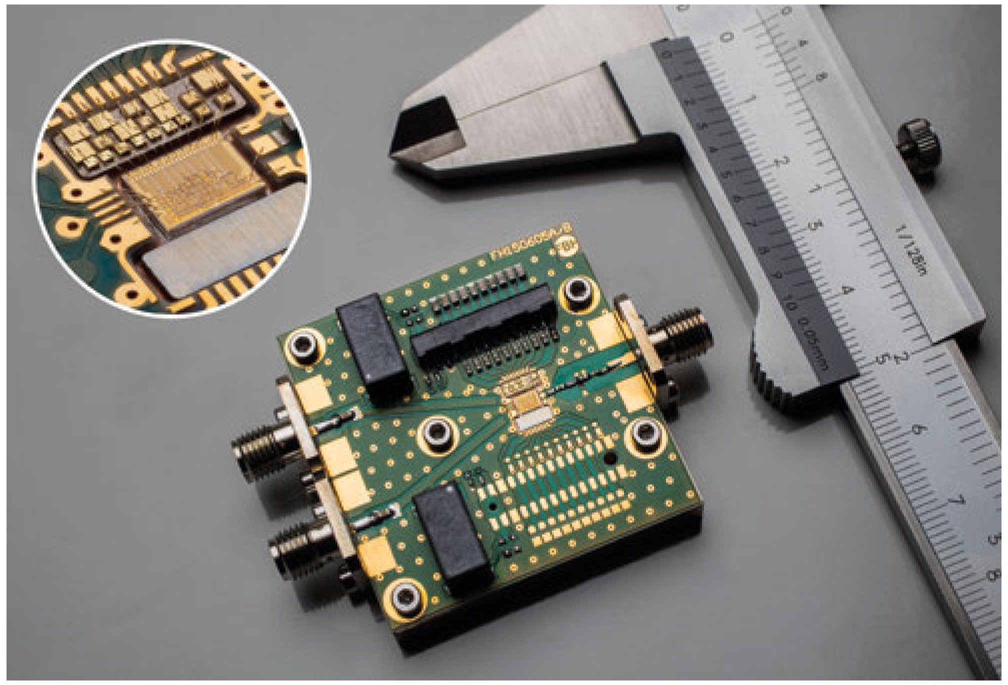
Um die technische Infrastruktur der Basisstationen fit für 5G zu machen, müssen die Hardware-Komponenten effizienter und flexibler werden. Das lässt sich unter anderem durch eine Erhöhung des digitalen Anteils erreichen. Im Fokus stehen dabei die Leistungsverstärker, da diese die Effizienz des Gesamtsystems und damit auch die Betriebskosten dominieren. Die bisherigen analogen Leistungsverstärker bieten nur eine geringe Effizienz und decken jeweils nur ein Frequenzband ab. Für unterschiedliche Kommunikationsstandards und Frequenzen werden bislang zusätzliche Module benötigt. Das FBH entwickelt daher seit einigen Jahren neue digitale Verstärkerarchitekturen, die ein effizientes Leistungsmanagement mit höchster Flexibilität verbinden und breitbandig arbeiten. Langfristiges Ziel ist der komplett digital realisierte Transmitter, bei dem ein Chip alle Frequenzbänder bedienen kann. Ergänzend untersucht das FBH leistungsfähige Modulations- bzw. Kodierungsverfahren, die die Eigenschaften von digitalen Verstärkern entscheidend beeinflussen. Das FBH hat dazu einen neuartigen Modulator entwickelt, der sich mit gängigen Digitalbausteinen realisieren lässt. Er erlaubt es zudem, Signale nach den verschiedensten Modulationsverfahren zu erzeugen.

Inzwischen erreichen digitale Leistungsverstärker aus dem FBH wettbewerbsfähige Werte hinsichtlich Gesamteffizienz und Linearität verglichen mit etablierten analogen Verstärkerkonzepten wie Doherty. Ein kürzlich am FBH entwickelter Leistungsverstärker bietet eine hohe Gesamteffizienz von mehr als 40 % bei 10 dB PAPR-Bandbreite – PAPR bezeichnet das Verhältnis von Spitzenleistung zu mittlerer Leistung eines Signals – im Bereich um 1 GHz.

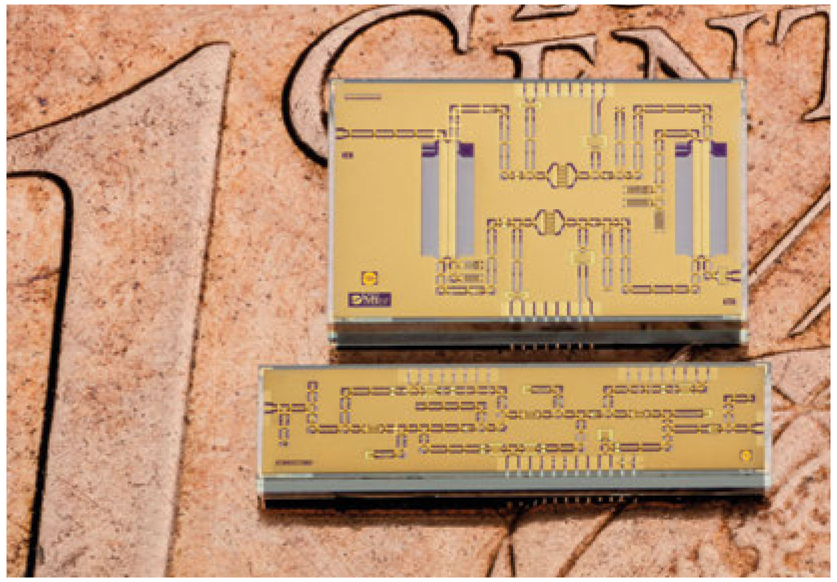
Eine weitere Variante der Digitalisierung von Leistungsverstärkern ist das Discrete Envelope Tracking (ET). Dabei wird die Versorgungsspannung des Endverstärkers variiert, um eine gute Energieeffizienz sicherzustellen – trotz der stark schwankenden momentanen Leistung bei modernen breitbandigen Modulationsverfahren. Beim Discrete Envelope Tracking wird diese Variation diskret realisiert, das heißt es wird nur zwischen mehreren konstanten Spannungswerten hin- und hergeschaltet. Diese digitalisierte Version des ET führt zu sehr effizienten und breitbandigen Lösungen. Am FBH wurden unlängst mit 160 MHz Modulations-Bandbreite bei einem 60 W Verstärker für 1,8 GHz neue internationale Bestwerte erreicht. Das ET-Konzept lässt sich auch vergleichsweise einfach auf Millimeterwellen-Verstärker übertragen, was für die 5G-Basisstationen entscheidend ist.

Die Frequenzgrenzen ausreizen – mit Terahertz-Leistungsverstärkern

Frequenzen im sub-Terahertz-Bereich rücken zunehmend in den Fokus, wenn es um die leistungsfähige Kommunikation der Zukunft geht. Drahtlose Übertragungsstrecken im Frequenzbereich zwischen 100 und 500 GHz sind notwendig, um das um Größenordnungen zunehmende Datenaufkommen für kurze Reichweiten bewältigen zu können. Weitere Anwendungen in



Novel digital power amplifier module generating signals by all kinds of modulation methods.
Neuartiges digitales Leistungsverstärker-Modul, das Signale nach verschiedensten Modulationsverfahren erzeugt.



GaN-based Ka-band amplifier chips.
GaN-basierte Ka-Band-Verstärkerchips.

diesem Frequenzbereich liegen in der Materialprüfung, in der Sicherheitstechnik bei Personen- und Gepäckkontrollen sowie der hochauflösenden Radartechnik für filigrane Robotik-Anwendungen. Alle diese Systemanwendungen erfordern elektronische Schaltkreise, die hohe Ausgangsleistungen im sub-Terahertz-Bereich liefern können – deren Realisierung ist mit konventioneller Halbleitertechnologie nicht möglich. Stattdessen muss das Halbleitermaterial Indiumphosphid (InP) eingesetzt werden. Am FBH entsteht im Rahmen der im April gestarteten BMBF-Initiative *Forschungsfabrik Mikroelektronik Deutschland (FMD)* eine Prozesslinie für integrierte Schaltungen mit InP-Transistoren. Auf modernsten Anlagen können dort InP-Schaltkreiswafer im industriellen Qualitätsmaßstab hergestellt werden.

Die Prozesslinie am FBH beinhaltet zudem die Option, im Rahmen der FMD gemeinsam mit dem Leibniz-Institut IHP die InP-Schaltungen auf Silizium-Wafer zu integrieren. Damit lassen sich die hohen Ausgangsleistungen von InP mit der Komplexität der Siliziumtechnologie kombinieren. Auf diese Weise können Höchstfrequenzmodule auf einem Chip realisiert werden, was für tragbare und kostengünstige System-Applikationen entscheidend ist.

Neuartige Transistoren erfolgreich im Wettbewerbsverfahren der Leibniz-Gemeinschaft

Künftige Mobilfunksysteme gehören auch zu den Anwendungsszenarien des Projektes *AlPower* (AlN electronics for a new generation of high-power devices), das das FBH Ende 2016 erfolgreich im Wettbewerbsfahren der Leibniz-Gemeinschaft eingeworben hat. Die Kombination von hohen Leistungen, hohen Spannungen und schneller Geschwindigkeit mit höchster Effizienz erfordert neuartige Leistungs- und Schalttransistoren. Aluminiumnitrid (AlN)-basierte Transistoren sollen diese Anforderungen erfüllen und für die besonders effiziente Energiekonversion in vielfältigen Anwendungen sorgen. Dazu zählen neben der mobilen Kommunikation und selbstfahrenden Autos auch die Energieversorgung im IT-Bereich und die industrielle Antriebstechnik.

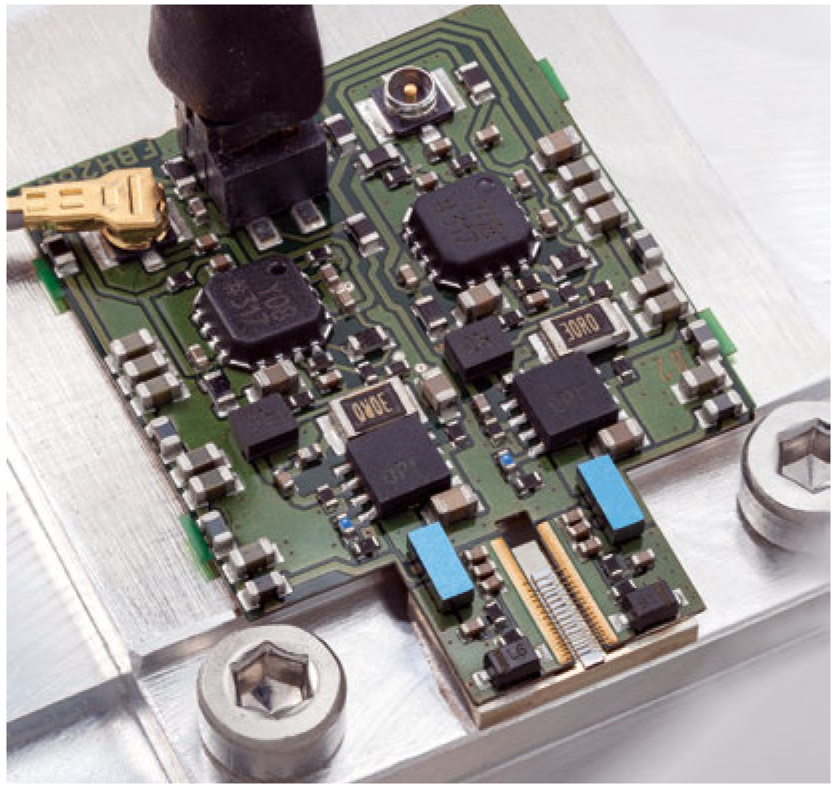
Dafür werden neuartige, besonders effiziente Transmitterlösungen benötigt, die auch bei Frequenzen jenseits von 20 GHz noch mit hohen Spannungen im 50-Volt-Bereich arbeiten können – dieser Frequenz- und Spannungsbereich ist mit herkömmlichen Galliumnitrid-basierten Transistoren nicht zugänglich. Die neuartigen HFETs (heterostructure field effect transistor) auf der Basis von Aluminiumnitrid sollen diese Begrenzung beseitigen. Mittels einer AlN/GaN/AlN-Halbleiterstruktur mit einer sehr dünnen AlN-Barriere sollen die Elektronen auch bei sehr hohen elektrischen Feldern auf den Transistorkanal begrenzt werden können. Dadurch sollen effiziente Hochleistungsverstärker > 20 GHz ebenso möglich sein wie effiziente 1200 Volt Schaltkonverter mit nie dagewesenen Geschwindigkeiten und Leistungsdichten. Abschließend soll ein 30-GHz-Prototyp mit 10 Watt Ausgangsleistung demonstriert werden, der die Frequenzbänder für die künftige Mobilkommunikation bedient. Zudem soll ein besonders kompakter 400 Volt Matrixkonverter für die Motorenregelung realisiert werden. Für die Entwicklungen in AlPower fließen in den nächsten drei Jahren 1,06 Millionen Euro ans FBH.

Strong demand for pulsed laser sources

For several years now, the Ferdinand-Braun-Institut has been developing novel laser sources that deliver short, high-precision pulses of variable duration in the range of 10 picoseconds to 100 nanoseconds. Other requirements to be met are high power, good beam quality, and high energy efficiency. These properties can all be tailored flexibly to the respective application.

Compact sources are key components in a wide range of applications, including materials processing, especially in conjunction with fiber optic amplifiers, for biomedical experiments based on fluorescence spectroscopy, and for mobile LIDAR systems. Such sources combine tailored diode laser technology for pulse generation with optimized RF microwave electronics components for control. These are both core competencies of FBH. The modules featuring integrated gallium nitride-based drivers achieve record values in terms of current and pulse width. Switched currents measure at 430 amperes for a 25 nanosecond pulse, or up to 30 amperes for a 0.4 nanosecond pulse.

Because demand for expertise in III-V electronics and optoelectronics is steadily growing, FBH is targetedly expanding this field. Future developments are primarily aimed at achieving shorter pulse durations while maintaining high currents.



Short-pulse laser with GaN transistors as driver, suited for applications such as LIDAR.
Kurzpulslaser mit GaN-Transistoren zur Ansteuerung für Anwendungen wie LIDAR.

Flexibly adaptable – from laser modules to operational laser systems

FBH develops light pulse sources from the laser module to the final laser system. Recently, an all-in-one system was presented that can be equipped with semiconductor components for the wavelengths 1030 nm and 1064 nm. Yet, the system can also be flexibly adapted to other wavelengths. It consists of a mode-coupled laser, an innovative pulse picker element, and an optical amplifier. The entire electronic control was developed at FBH and uses proprietary gallium nitride transistors. By using these transistors, short pulses can be flexibly selected from a single pulse to several sequential pulses (burst mode) and amplified. The all-in-one system is computer-controlled, making it very easy to integrate into all kinds of laser systems. This ensures stable and user-friendly operation.

For the first time worldwide, a tailored DFB laser chip and high current density drive circuitry were integrated into a butterfly housing. These electronics allow very precise and ultra-short current pulses of up to 6 amperes to be produced at pulse widths in the nanosecond range. The optical pulses reach an output power in excess of 3 watts and boast a narrow linewidth.

Stark nachgefragt – gepulste Strahlquellen

Das Ferdinand-Braun-Institut entwickelt seit mehreren Jahren neuartige Laserquellen, die kurze, hochpräzise und in der Dauer variable Pulse im Bereich von 10 Pikosekunden bis 100 Nanosekunden liefern. Zusätzlich sind hohe Leistung, gute Strahlqualität und hohe Energieeffizienz gefragt. Ihre Eigenschaften können flexibel auf die jeweilige Anwendung zugeschnitten werden.

Die kompakten Quellen sind Schlüsselkomponenten für ein breites Spektrum von Applikationen, unter anderem in der Materialbearbeitung, vor allem in Verbindung mit Faserverstärkern, für biomedizinische Untersuchungen auf Basis der Fluoreszenzspektroskopie und für mobile LIDAR-Systeme. Sie verbinden ein maßgeschneidertes Design für die Impulserzeugung aus der Diodenlasertechnologie mit optimierten Hochfrequenz-Komponenten der Mikrowellenelektronik für die Ansteuerung. Beides sind Kernkompetenzen des FBH. Die Module mit integrierten Galliumnitrid-basierten Treibern erreichen Spitzenwerte in Bezug auf Strom und Pulsweite. Es werden Ströme von 430 Ampere mit Pulslängen von 25 Nanosekunden beziehungsweise von bis zu 30 Ampere in 0,4 Nanosekunden geschaltet.

Da dieses Know-how aus III/V-Elektronik und Optoelektronik immer stärker nachgefragt ist, wird dieser Bereich nun gezielt ausgebaut. Künftige Entwicklungen zielen vor allem auf kürzere Pulsdauern bei weiterhin hohen Strömen.

Picosecond light source with integrated pulse picker.
Pikosekunden-Lichtquelle mit integriertem Pulspicker.

Flexibel anpassbar – vom Lasermodul bis zum einsatzfähigen Lasersystem
Das FBH entwickelt derartige Lichtimpulsquellen vom Lasermodul bis zum fertigen Lasersystem. Erst kürzlich wurde ein All-in-One-System vorgestellt, das mit Halbleiterkomponenten für die Wellenlängen 1030 nm und 1064 nm bestückt werden kann. Das System lässt sich flexibel auf andere Wellenlängen übertragen. Es besteht aus einem modengekoppelten Laser, einem innovativen Pulspicker-Element sowie einem optischen Verstärker. Die komplette elektronische Ansteuerung wurde am FBH entwickelt und nutzt selbst entwickelte Galliumnitrid-Transistoren. Durch Einsatz dieser Transistoren können kurze Impulse flexibel vom Einzelpuls bis zu mehreren aufeinander folgenden Pulsen (burst mode) selektiert und verstärkt werden. Das All-in-One-System wird computergesteuert betrieben, sodass es einfach in verschiedenste Lasersysteme integriert werden kann. Dies sichert den stabilen und nutzerfreundlichen Betrieb.

Weltweit erstmalig wurden zudem in ein Butterflygehäuse ein maßgeschneiderter DFB-Laserchip und eine Hochfrequenz-Schaltungselektronik integriert. Diese Elektronik ermöglicht es, sehr präzise und ultrakurze Stromimpulse bis 6 Ampere mit Impulsbreiten im Nanosekunden-Bereich zu erzeugen. Die optischen Impulse erreichen eine Ausgangsleistung von mehr als 3 Watt und bieten eine geringe Linienbreite.

Peak powers – efficient diode lasers with high power and beam quality

In its High-Power Diode Lasers Lab, FBH develops tailored diode lasers for applications such as pumping of solid-state lasers or for direct application in materials processing and medical technology. Focal points of optoelectronic research in this area are power, efficiency, beam quality, narrow spectral linewidths, and reliability of high-power diode lasers. A comprehensive understanding of these parameters and their limitations is indispensable if the power of diode lasers is to be increased any further.

Currently, FBH is working to continually improve the properties of diode lasers in standard configurations. Examples are 1 cm laser bars with higher efficiency that deliver output powers in the kilowatt range, or 100 µm aperture single emitters that emit within a narrow spatial angle.

FBH is additionally studying novel device concepts, such as a technology for monolithic wavelength stabilization. In the EU project *BRIDLE*, for example, novel single emitter designs and an innovative grating technology are being combined with advanced, integrated mini-arrays – allowing for especially efficient and economical laser beam combining.

***BRIDLE* – brilliant high-power diode lasers for industry**
After four years of research, the *BRIDLE* project (BRilliant Industrial Diode LasEr) funded by the European Union was successfully concluded in 2016. As the culmination of the project, the partners demonstrated a direct machining system for cutting metal. FBH developed the diode laser chips required for this, which increased the brilliance by a factor of 2 above the previous state of the art. Combining this with an innovative monolithically integrated grating technology allowed the system brilliance to be increased even further.

"The aim was to introduce a maximum of power into a high-brilliance laser beam with highest efficiency," explains FBH project manager Paul Crump. "Diode lasers are the most energy-efficient and thus very environmentally friendly laser beam sources. They can also be affordably mass produced, where thousands are processed together on a single wafer, and they can be integrated into tiny, yet highly reliable modules." Aside from using them merely as pump sources, as so far, the miniature diode lasers will now be used directly for material processing in high-brilliance applications such as steel cutting. A laser is considered brilliant if its beam can be focused into a tiny dot of only 0.1 millimeter at a distance of one meter. While the fiber-optic, solid-state and carbon dioxide lasers used so far achieve the necessary power density and brilliance, they consume a great deal of energy. They only have a maximum efficiency of approximately 35 to 40 %.

The *BRIDLE* project broke multiple records. FBH improved the epitaxy design and optimized the processing enough to reduce the width of the emitter from the previous standard of 100 microns down to 30 microns – without major loss of efficiency or power. Compared to the former state of the art, FBH managed to double the brilliance of the laser beam, so important in industry, thereby allowing better focusing to a tiny dot and thus considerably improving the metal-cutting performance. FBH also developed new chip structures that allow efficient and affordable beam combining. To do this, a novel monolithic grating was introduced into the high-brilliance, narrow DFB diode lasers to stabilize and optimize the wavelengths. Thus, for the first time, it is possible to produce a brilliant beam of simultaneously narrow spectrum (<1 nm), high power (5 W), and high efficiency (50 %). The diode lasers developed at FBH present a technological advantage that is crucial in the global market.

Kilowatt-class high-power diode laser bar.
Hochleistungs-Diodenlaserbarren der Kilowatt-Klasse.

Spitzenleistungen – effiziente Diodenlaser mit höchster Leistung und Strahlqualität

Für Anwendungen wie etwa zum Pumpen von Festkörperlasern sowie für den direkten Einsatz in der Materialbearbeitung und der Medizin entwickelt das FBH in seinem High-Power Diode Laser Lab maßgeschneiderte Diodenlaser. Leistung, Effizienz, Strahlgüte, schmale spektrale Linienbreite und Zuverlässigkeit dieser Hochleistungs-Diodenlaser sind Schwerpunkte der optoelektronischen Forschung in diesem Bereich. Ein umfassendes Verständnis dieser Parameter und ihrer Limitationen ist unerlässlich, um die Leistungsfähigkeit der Diodenlaser weiter steigern zu können.

Aktuell arbeitet das FBH daran, die Eigenschaften von Diodenlasern in Standard-Konfigurationen stetig zu verbessern. Dazu zählen beispielsweise 1 cm Laserbarren mit verbesserter Effizienz, die Ausgangsleistungen im Kilowatt-Bereich liefern, oder Einzelemitter mit 100 µm Apertur, die in einen engen Raumwinkel emittieren.

Zusätzlich untersucht das FBH neuartige Bauelementkonzepte wie etwa eine Technologie zur monolithischen Wellenlängenstabilisierung. So wurden beispielsweise im EU-Projekt *BRIDLE* neuartige Einzelemitter-Designs und eine innovative Gittertechnologie mit hochentwickelten, integrierten Miniarrays kombiniert – auf diese Weise lässt sich der Laserstrahl besonders effizient und kostengünstig kombinieren.

BRIDLE – brillante Hochleistungs-Diodenlaser für die Industrie

Nach 4-jähriger Forschungsarbeit wurde das von der Europäischen Union geförderte Projekt *BRIDLE* (BRilliant Industrial Diode LasEr) im Jahr 2016 erfolgreich abgeschlossen. Im Ergebnis demonstrierten die Projektpartner ein System zur Direktbearbeitung, mit dem Metall geschnitten wurde. Das FBH entwickelte die dafür benötigten Diodenlaserchips, mit denen die Brillanz um den Faktor 2 gegenüber dem Stand der Technik erhöht wurde. Durch Kombination mit einer neuartigen monolithisch integrierten Gittertechnologie konnte die Systembrillanz weiter erhöht werden.

„Ziel war es, ein Maximum an Leistung mit höchster Effizienz in einen hochbrillanten Laserstrahl einzubringen", erklärt FBH-Projektleiter Paul Crump. „Diodenlaser sind die energieeffizienteste und damit eine sehr umweltfreundliche Laserstrahlquelle. Sie sind zudem preiswert in der Massenproduktion, da sie zu Tausenden auf einem Wafer prozessiert werden und sich in kleine, besonders zuverlässige Module integrieren lassen." Statt bislang nur als Pumpquellen sollen die kleinen Diodenlaser künftig direkt zur Materialbearbeitung in hochbrillanten Anwendungen wie etwa zum Schneiden von Stahl eingesetzt werden. Ein Laser gilt dann als brillant, wenn sein Strahl über eine Distanz von einem Meter auf einen winzigen Punkt von nur 0,1 Millimeter fokussiert werden kann. Die bisher eingesetzten Faser-, Festkörper- oder Kohlendioxidlaser erreichen zwar die notwendige Leistungsdichte und Brillanz, verbrauchen aber viel Energie; sie haben lediglich eine maximale Effizienz von ca. 35 bis 40 %.

Laser system using FBH diode lasers cutting sheet metal, developed within EU project *BRIDLE*.
Lasersystem mit FBH-Diodenlasern, das im EU-Projekt *BRIDLE* entwickelt wurde, beim Schneiden von Metall.

Im *BRIDLE*-Projekt gab es gleich mehrere Rekorde zu vermelden. So hat das FBH das Epitaxie-Design verbessert und die Prozessierung so optimiert, dass die bisherige Standardbreite der Emitter von 100 Mikrometern auf 30 reduziert werden konnte – ohne größere Abstriche bei Effizienz und Leistung. Dadurch lässt sich die für die Industrie so wichtige Brillanz des Laserstrahls gegenüber dem bisherigen Stand der Technik verdoppeln, was zu einer besseren Fokussierung auf einen winzigen Punkt führt und damit das Schneiden von Metallen deutlich verbessert. Das FBH entwickelte zudem neue Chipstrukturen, mit denen sich der Strahl effizient und kostengünstig kombinieren lässt. Dafür wurde in die hochbrillanten schmalen DFB-Diodenlaser ein neuartiges monolithisches Gitter eingebracht, das die Wellenlänge stabilisiert und optimiert. Damit ist es erstmals möglich, in einem brillanten Strahl gleichzeitig ein schmales Spektrum (<1 nm), eine hohe Leistung (5 W) und einen hohen Wirkungsgrad (50 %) zu realisieren. Die am FBH entwickelten Diodenlaser ermöglichen einen technologischen Vorsprung, der für den Weltmarkt entscheidend ist.

Combined expertise – FBH develops tailored light sources in the Leibniz Research Alliance *Health Technologies*

FBH has been contributing its expertise in laser light sources to the Leibniz Research Alliance *Health Technologies* since 2014. This association of 15 research institutes develops technological solutions for urgent medical issues and unites expertise in multiple scientific fields, from photonics and medicine to microelectronics and materials research, to economic research and applied mathematics. Innovative health technologies can thus be brought to market maturity along a gapless innovation chain of industry, clinics, insurance companies, and politics. *Leibniz Health Technologies* takes a comprehensive approach that includes researching the economic, social, and ethical consequences of new technologies. FBH is currently involved in the two Research Alliance projects *EXASENS* and *HYPERAM*.

EXASENS – point-of-care sensor platform for chronic inflammatory respiratory diseases

Since January 2016, FBH and eight other partners from the Leibniz Research Alliance *Health Technologies* have been collaborating in the *EXASENS* project to research point-of-care (POC) technology for predicting and diagnosing chronic inflammatory respiratory diseases such as asthma or chronic obstructive pulmonary disease, COPD. According to the journal "Pneumologie", there are nearly 12 million suffers of these diseases in Germany alone. The Alliance is backed by 6.25 million Euros from the German Federal Ministry of Education and Research (BMBF).

Prediction or early detection of acute, attack-like exacerbations by telemedicine-capable POC diagnosis systems could reduce the necessity for intensive medical measures and also improve prognoses. The ultimate goal is to have POC systems readily available for rapid intervention in acute situations, for individualized treatment, and for closely networked monitoring of disease progression and treatment, thereby significantly helping to improve quality of life.

FBH is developing the necessary compact light sources, and thus a key component, for the POC system which, among other things, employs Shifted Excitation Resonance Raman Difference Spectroscopy (SERRDS). The diode laser modules, which emit at 532 nm wavelength, deliver two excitation lines at a close spectral distance of about 10 cm^{-1}. When measuring two Raman spectra with excitation wavelengths at this distance, Raman signals can be separated from interfering signals such as fluorescence or ambient light. A particular requirement for the light source, which is only about half the size of a box of matches, is rapid spectral switching capability for the excitation wavelength. This, in turn, allows for much shorter measuring times and thus faster diagnoses than ever before.

SERRDS requires precise adjustment of the properties of two active components in the system: the diode laser as pump light source, and the crystal for non-linear frequency conversion.

Because such SHG crystals are third-party components, the diode laser must be precisely adjustable to accommodate any manufacturers' tolerances in the crystals. This demands utmost precision in the manufacture of the wavelength-stabilizing grating and in the lateral design of the waveguide in the semiconductor chip. Heating elements are also installed to allow precise adjustment of the wavelength by altering the temperature of the grating section. Switching between the two wavelengths is done directly via the active gain section.

HYPERAM – imaging method for rapid tissue diagnosis

In the Leibniz Research Network *HYPERAM*, three Leibniz institutes have joined forces from the fields of biosciences, astrophysics, electronics, and medicine. They are combining their interdisciplinary knowledge in order to develop rapid, label-free and non-invasive tissue diagnosis methods based on wide-field Raman imaging. This will open up new possibilities for clinically evaluating tissue already during surgery using functional Raman images to reveal tumor margins. This would make for shorter and more precise surgical operations in oncology, for example. Among other things, the project aims to translate the method of integral field spectroscopy, which was born from astrophysics and is normally used to study large areas of the night sky, to biomedical imaging applications. The overall project started in 2016 and is planned to run for three years with approximately one million Euros in funding from the Leibniz competition.

In this project, FBH is again developing the Raman-based diode lasers optimized for tissue diagnosis, as an important centerpiece of the system. The challenge lies in combining the high laser powers required for imaging with the spectral characteristics needed for spectroscopy and SERRDS. At the same time, the maximum permissible radiation doses must not be exceeded. FBH is therefore taking two approaches: it is developing a light source of 785 nm wavelength and up to 4 watt output power, plus a second beam source in the blue-green spectral range of 457 nm wavelength – a frequency range in which strong fluorescence occurs. This light source should be suitable for the SERRDS method and thus allow the separation of Raman signals and fluorescence for the imaging method as well.

Geballte Kompetenz – FBH entwickelt maßgeschneiderte Lichtquellen im Leibniz-Forschungsverbund Gesundheitstechnologien

Das FBH bringt sein Know-how bei Laserlichtquellen seit 2014 im Forschungsverbund *Leibniz Gesundheitstechnologien* ein. Der Verbund aus 15 Forschungseinrichtungen erarbeitet Technologie-Lösungen für drängende medizinische Fragestellungen und vereint Kompetenzen aus verschiedenen Wissenschaftsbereichen, von Photonik und Medizin über Mikroelektronik und Materialforschung bis hin zur Wirtschaftsforschung und angewandten Mathematik. Neuartige Gesundheitstechnologien können so mit Industrie, Kliniken, Versicherungen und Politik entlang einer lückenlosen Innovationskette zur Marktreife geführt werden. *Leibniz Gesundheitstechnologien* setzt dabei auf einen ganzheitliches Konzept und erforscht auch ökonomische, soziale und ethische Folgen neuer Technologien. Das FBH ist aktuell in die beiden Verbund-Projekte *EXASENS* und *HYPERAM* eingebunden.

EXASENS – Point-of-Care-Sensorplattform für chronisch-entzündliche Atemwegserkrankungen

Das FBH und acht weitere Partner aus dem Forschungsverbund *Leibniz Gesundheitstechnologien* arbeiten seit Januar 2016 gemeinsam im Verbundprojekt *EXASENS* an der Erforschung einer Point-of-Care-Technologie (POC) zur Vorhersage und Diagnose von chronisch-entzündlichen Atemwegserkrankungen wie etwa Asthma oder der chronisch-obstruktiven Lungenerkrankung COPD. Daran leiden nach Angaben des Fachblatts „Pneumologie" alleine in Deutschland knapp 12 Millionen Menschen. Der Verbund wird vom Bundesministerium für Bildung und Forschung (BMBF) mit 6,25 Millionen Euro gefördert.

Blue-emitting diode laser suited for Shifted Excitation Resonance Raman Difference spectroscopy.
Blau-emittierender Diodenlaser, der sich für die Shifted Excitation Resonance Raman Difference Spektroskopie eignet.

Die Vorhersage oder Frühdiagnose von akuten, anfallartigen Verschlimmerungen (Exazerbationen) durch telemedizinfähige POC-Diagnose-Systeme könnte daher die Notwendigkeit intensivmedizinischer Maßnahmen reduzieren und die Prognose verbessern. Am Ende sollen POC-Systeme bereitstehen, die ein rasches Eingreifen bei Akutsituationen, eine individualisierte Behandlung sowie ein engmaschiges Verlaufs- und Therapiemonitoring ermöglichen und so einen wesentlichen Beitrag zur Verbesserung der Lebensqualität leisten.

Das FBH entwickelt die dafür benötigten kompakten Lichtquellen – und damit eine Schlüsselkomponente für das POC-System, das unter anderem die Shifted Excitation Resonance Raman Difference Spectroscopy (SERRDS) anwendet. Die Diodenlasermodule, die bei 532 nm Wellenlänge emittieren, liefern zwei Anregungslinien in einem engen spektralen Abstand von etwa 10 cm^{-1} – bei Messung zweier Raman Spektren mit Anregungswellenlängen dieses Abstandes lassen sich Raman-Signale von Störsignalen wie Fluoreszenz oder Umgebungslicht separieren. Eine besondere Anforderung an die Lichtquelle, die nur etwa so groß wie eine Streichholzschachtel ist, ist die Möglichkeit zum schnellen spektralen Umschalten der Anregungswellenlänge. Das wiederum ermöglicht deutlich kürzere Messzeiten als bisher und damit auch schnellere Diagnosen.

SERRDS erfordert die genaue Anpassung der Eigenschaften der beiden aktiven Komponenten des Systems: des Diodenlasers als Pumplichtquelle und des Kristalls zur nichtlinearen Frequenzkonversion. Da derartige SHG-Kristalle Zukaufkomponenten sind, muss der Diodenlaser trotz möglicher Herstellertoleranzen bei den Kristallen präzise einstellbar sein. Dies erfordert höchste Präzision bei der Herstellung Wellenlängen-stabilisierender Gitter und beim lateralen Design der Wellenleiter im Halbleiterchip. Zusätzlich sind Heizelemente vorgesehen, mit denen die Wellenlänge präzise über die Temperatur an der Gittersektion angepasst werden kann. Das Umschalten zwischen den zwei Wellenlängen erfolgt direkt über die aktive Gewinnsektion.

HYPERAM – bildgebende Verfahren zur schnellen Gewebediagnostik

Im Leibniz-Forschungsnetzwerk *HYPERAM* haben sich drei Leibniz-Institute aus den Bereichen Biowissenschaften, Astrophysik, Elektronik sowie Medizin, zusammengetan. Sie bündeln ihr interdisziplinäres Wissen, um eine schnelle, färbefreie und nichtinvasive Gewebediagnostik zu entwickeln, die auf einer Weitfeld-Raman-Bildgebung basiert. Dies eröffnet neue Möglichkeiten, Gewebe noch während eines operativen Eingriffs mit funktionellen Raman-Bildern zur Darstellung von Tumorrändern klinisch zu bewerten. Das verkürzt und präzisiert chirurgische Interventionen, etwa in der Krebsmedizin. Dazu soll unter anderem das in der Astrophysik etablierte Verfahren der integralen Feldspektroskopie, mit dem üblicherweise große Bereiche des Sternenhimmels untersucht werden, auf bildgebende biomedizinische Anwendungen übertragen werden. Das auf drei Jahre angelegte und mit gut einer Million Euro aus dem Leibniz-Wettbewerb geförderte Gesamtprojekt wurde 2016 gestartet.

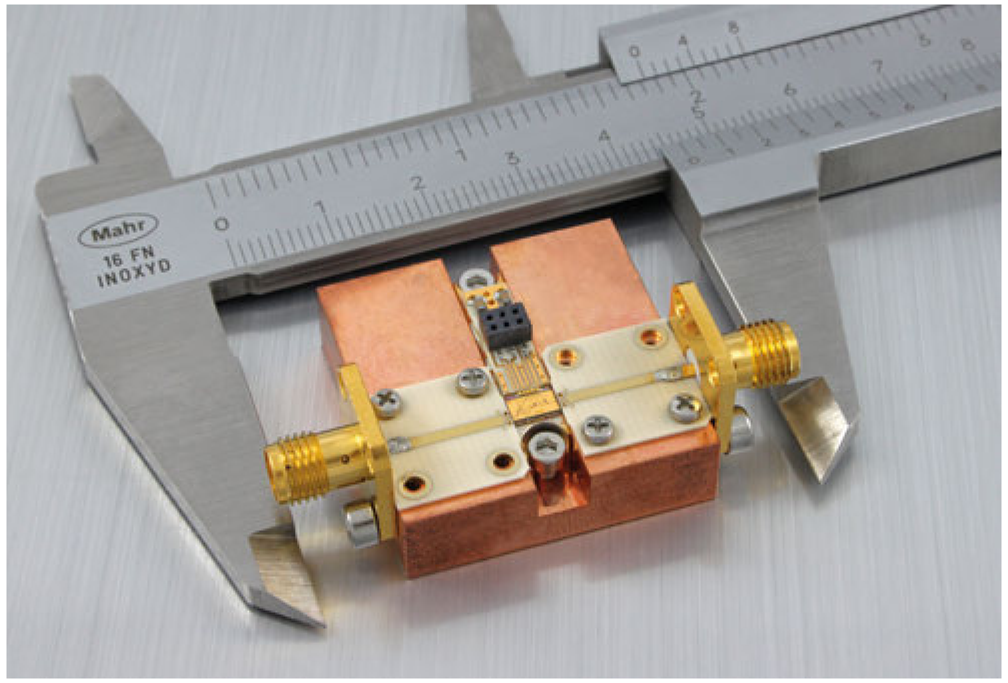
Das FBH entwickelt auch hier die auf Gewebediagnostik optimierten Raman-basierten Diodenlaser als wichtige Herzstücke des Systems. Die besondere Anforderung besteht darin, die für die Bildgebung erforderlichen höheren Laserleistungen mit den für die Spektroskopie und SERRDS benötigten spektralen Eigenschaften zu kombinieren. Gleichzeitig dürfen die maximal zulässigen Bestrahlungsdosen nicht überschritten werden. Das FBH verfolgt daher zwei Ansätze und entwickelt eine Lichtquelle bei 785 nm Wellenlänge mit einer Ausgangsleistung bis zu 4 Watt. Zusätzlich wird eine zweite Strahlquelle im blau-grünen Spektralbereich mit 457 nm Wellenlänge entwickelt – ein Frequenzbereich, in dem starke Fluoreszenz auftritt. Diese Lichtquelle soll sich für das SERRDS-Verfahren eignen und somit die Trennung von Raman-Signalen und Fluoreszenz auch für das bildgebende Verfahren ermöglichen.

Fifth Joint Lab – FBH combines expertise in low-noise amplifiers

In its fifth Joint Lab BTU-CS – FBH Microwave, FBH unites its expertise in low-noise amplifiers and transistor modeling with the expertise of Brandenburg University of Technology Cottbus-Senftenberg (BTU-CS). The Joint Lab is directed by Matthias Rudolph, who has held the Ulrich-L.-Rohde Chair for RF and Microwave Techniques at BTU Cottbus-Senftenberg since 2009 and who previously worked for ten years at FBH.

A main focus of the joint research here is on robust, low-noise amplifiers that are a key component in wireless receivers. These amplify the received signals for further processing – without disrupting the signals with their own noise. Certain switching concepts, for example, need to be improved to make the amplifiers more sensitive to and at the same time more robust against interfering signals. The work is tightly networked in this Joint Lab: the switching concepts are being developed at BTU Cottbus-Senftenberg, while the chips are being manufactured, set up and tested at FBH.

A second focus is transistor modeling, for precisely describing the electrical and thermal behavior of the new transistors being developed at FBH. This provides the basis for designing circuits on the computer. The Ulrich-L.-Rohde Foundation supported the establishment of an RF measurement laboratory, which will become part of the Joint Lab as a perfect complement to the existing resources at FBH.



Monolithically integrated low-noise amplifier in test fixture.
Monolithisch-integrierter rauscharmer Verstärker in Testfassung.

The Joint Labs are a proven model of cooperation, by which FBH networks basic research with applied research and gives junior academics the opportunity to write application-oriented bachelor's, master's and doctoral theses. FBH collaborates in other Joint Labs with Technische Universität Berlin, Humboldt-Universität zu Berlin, and Goethe University Frankfurt.

Fünftes Joint Lab – FBH bündelt Kompetenzen bei rauscharmen Verstärkern

In seinem fünften Joint Lab BTU-CS – FBH Microwave bündelt das FBH seine Kompetenzen bei rauscharmen Verstärkern und bei der Transistormodellierung mit der Brandenburgischen Technischen Universität Cottbus-Senftenberg (BTU-CS). Geleitet wird das Joint Lab von Matthias Rudolph, der seit 2009 Inhaber der Ulrich-L.-Rhode Stiftungsprofessur für Hochfrequenz- und Mikrowellentechnik an der BTU Cottbus-Senftenberg ist und zuvor über zehn Jahre am FBH beschäftigt war.

Ein wesentlicher Fokus der gemeinsamen Forschungsarbeiten liegt auf robusten rauscharmen Verstärkern, die eine wichtige Komponente in Funkempfängern sind. Sie verstärken die empfangenen Signale, um sie weiter zu verarbeiten – ohne durch ihr eigenes Rauschen zu stören. So sollen Schaltungskonzepte verbessert werden, um die Verstärker empfindlicher und gleichzeitig robuster gegenüber Störsignalen zu machen. Die Arbeiten sind eng vernetzt: An der BTU Cottbus-Senftenberg entstehen die Schaltungskonzepte, die Chips werden am FBH gefertigt, aufgebaut und vermessen.

Ein zweiter Schwerpunkt liegt auf der Modellierung von Transistoren, mit der das elektrische und thermische Verhalten der am FBH entwickelten neuen Transistoren präzise beschrieben wird. Das liefert die Grundlagen für den Schaltungsentwurf am Computer. Die Ulrich-L.-Rhode Stiftung hat den Aufbau eines Hochfrequenz-Messlabors an der BTU Cottbus-Senftenberg unterstützt, das Bestandteil des Joint Labs wird und die Ressourcen am FBH optimal ergänzt.

Mit dem bewährten Kooperationsmodell der Joint Labs vernetzt das FBH grundlagen- und anwendungsorientierte Forschung und ermöglicht dem akademischen Nachwuchs anwendungsnahe Bachelor-, Master- und Promotionsarbeiten. Weitere Joint Labs unterhält das FBH gemeinsam mit der Technischen Universität Berlin, der Humboldt-Universität zu Berlin sowie mit der Goethe-Universität Frankfurt.

Cooperative projects and research services secure the competitiveness of enterprises

FBH offers its expertise to partners from research and industry in many ways, including in the scope of research cooperatives and R&D services. The spectrum of cooperation partners ranges from global players like TRUMPF, OSRAM and Bosch to small and mid-sized enterprises (SME). FBH is an indispensable partner in the value chain for SMEs, in particular, since a mid-sized enterprise can hardly economically run a high-performance and accordingly expensive infrastructure such as a cleanroom complete with special high-tech equipment.

Cooperation with the company sglux SolGel Technologies GmbH, now located in Adlershof, has been repeatedly extended and expanded over the years. Having begun in 2008 with an R&D project to develop a production method for UV photodiodes, FBH now manufactures all photodiodes for the company. In other joint R&D projects, FBH is continually making enhancements to radiation-hardened UV detector chips. These provide the basis for sglux components for measuring ultraviolet radiation. The company's success is reflected not only in its steadily increasing turnover and employee numbers, but also in the construction of its own 1,000 square-meter office and manufacturing building. Completion is planned for August 2017.

The spin-off eagleyard Photonics also procures its laser chips from FBH. The company offers various designs of fully assembled diode lasers with defined characteristics. Applications range from material processing and metrology to medical technology and analytics. In addition to laser diodes for well-established applications, FBH is continually developing laser

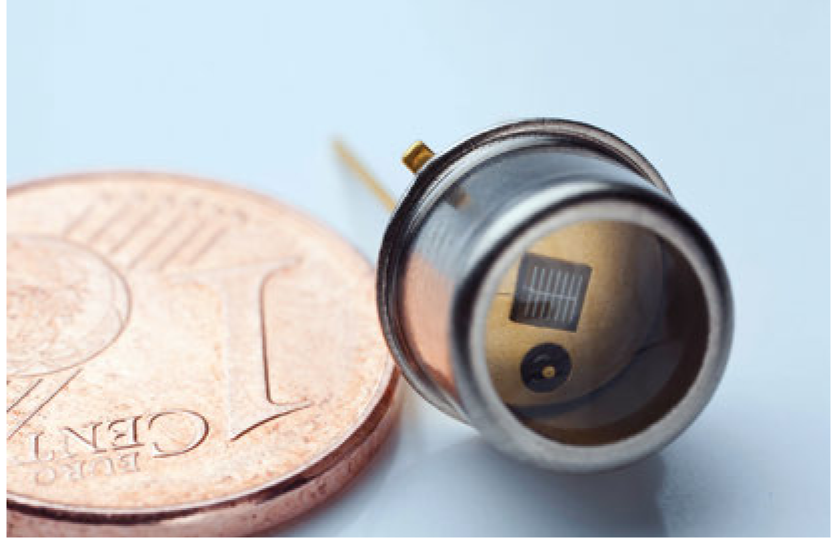


Photo diodes like this are marketed by the industrial partner sglux.
Fotodioden wie diese werden vom Industriepartner sglux vermarktet.

diodes with customized and application-specific properties in the scope of research assignments. These are subsequently marketed by eagleyard.

FBH frequently carries out substeps as research contracts. An example of this is the ion implantation process FBH does for companies of the Jenoptik Group as an important process step in the insulation of semiconductors. For its cooperation partner Lumics, FBH processes modules by lithography and etching. Another example is coating and etching for the Berlin company OSA Opto Light. FBH cooperates with TRUMPF in the field of mounting and assembly.

Field-tested products: application development

Another aspect of research cooperatives and services is application development. FBH supports SMEs from the region in particular on the development and refinement of their products. Practical testing throughout the ongoing research process yields important feedback for the optimization of their products – and thus a key competitive advantage. In many cases, these companies are world leaders in niche markets for highly specialized devices and software.

For example, FBH has been successfully cooperating for many years with the Adlershof-based company SENTECH Instruments. In its application laboratory for plasma technologies at FBH, the company develops sophisticated etching processes in particular for III-V semiconductors (GaAs, InP, and GaN). This way, systems can be demonstrated to the expert audience directly on site. SENTECH also commissions technology transfer services, which flow directly into SENTECH's technological developments. These provide the basis for future innovations in the field of plasma etching and deposition technology.

FBH also cooperates closely with the Berlin company LayTec. FBH and LayTec jointly tested and perfected the in situ curvature sensor EpiCurve. The software program EpiNet also underwent practical testing at FBH. The system monitors wafer curvature very precisely and directly on site during the epitaxy of electronic and optoelectronic components. Wafers for gallium nitride-based components, e.g. for light-emitting diodes (LEDs), are often greatly curved due to the nature of the materials. Targetedly controlling wafer curvature already during the epitaxy process can greatly minimize this curvature. In tests at FBH, wafer curvature has even been monitored in situ during plasma etching, yielding important insights for process control. This considerably raises both quality and yield of devices.

Forschungskooperationen und -dienstleistungen sichern Wettbewerbsfähigkeit von Unternehmen

Das FBH macht sein Know-how Partnern aus Forschung und Industrie in vielfältigen Formen zugänglich, unter anderem im Rahmen von Forschungskooperationen und F&E-Dienstleistungen. Das Spektrum der Kooperationspartner reicht dabei von Global Playern wie TRUMPF, OSRAM und Bosch bis hin zu kleinen und mittleren Unternehmen (KMU). Gerade für KMUs ist das FBH ein unverzichtbarer Partner in der eigenen Wertschöpfungskette, da eine leistungsfähige und damit teure Infrastruktur wie ein Reinraum mit spezieller Ausrüstung und Anlagentechnik für mittelständische Unternehmen kaum wirtschaftlich zu betreiben ist.

Die Zusammenarbeit mit dem inzwischen in Adlershof ansässigen Unternehmen sglux SolGel Technologies GmbH beispielsweise wurde im Laufe der Jahre immer weiter ausgebaut: 2008 gestartet mit einem F&E-Projekt zur Entwicklung eines Produktionsverfahrens für UV-Fotodioden, stellt das FBH inzwischen sämtliche Fotodioden für das Unternehmen her. Im Rahmen weiterer gemeinsamer F&E-Projekte wurden die strahlungsharten UV-Detektorchips kontinuierlich weiterentwickelt. Diese Bauelemente sind die Basis für die Komponenten von sglux zur Messung von ultravioletter Strahlung. Damit ist das Unternehmen inzwischen so erfolgreich, dass nicht nur Umsatz und Personal stetig gewachsen sind, sondern aktuell ein eigenes Büro- und Fertigungsgebäude mit rund 1.000 Quadratmetern errichtet wird. Die Fertigstellung ist für August 2017 geplant.

eagleyard
photonics

Auch die Ausgründung eagleyard Photonics bezieht seine Laserchips vom FBH. Das Unternehmen bietet fertig aufgebaute Diodenlaser in verschiedenen Bauformen mit spezifischen Eigenschaften an. Die Anwendungen reichen von der Materialbearbeitung und Metrologie bis hin zu Medizintechnik und Analytik. Neben Laserdioden für etablierte Anwendungen werden im Rahmen von Forschungsaufträgen vom FBH immer wieder Laserdioden mit kunden- und anwendungsspezifischen Eigenschaften entwickelt. Sie werden anschließend von eagleyard vermarktet.

Häufig werden Teilschritte als Forschungsaufträge an das FBH vergeben. Dazu zählt etwa die Ionenimplantation, die als wichtiger Prozess zur Isolation von Halbleitern für Firmen der Jenoptik-Gruppe durchgeführt wird. Für den Kooperationspartner Lumics werden am FBH Module mit Lithografie- und Ätzschritten prozessiert. Weitere Beispiele sind die Durchführung von Beschichtungs- und Ätzprozessen für das Berliner Unternehmen OSA Opto Light. Mit Trumpf arbeitet das FBH auf dem Gebiet der Aufbau- und Verbindungstechnik zusammen.

Plasma etching process in FBH's cleanroom.
Plasma-Ätzprozess im FBH-Reinraum.

Produkte im Praxistest: Applikationsentwicklung

Ein weiterer Aspekt bei Forschungskooperationen und -dienstleistungen ist die Applikationsentwicklung. Das FBH unterstützt insbesondere KMU aus der Region bei der Entwicklung und Verbesserung ihrer Produkte. Durch den Praxistest im laufenden Forschungsprozess erhalten sie wichtige Rückmeldungen zur Optimierung ihrer Produkte – und somit einen entscheidenden Wettbewerbsvorteil. Häufig sind diese Unternehmen Weltmarktführer von hochspezialisierten Geräten und Software in Nischenmärkten.

So kooperiert das FBH seit vielen Jahren erfolgreich mit der Adlershofer Firma SENTECH Instruments. In ihrem Applikationslabor für Plasmatechnologien am FBH entwickelt das Unternehmen anspruchsvolle Ätzprozesse insbesondere für III/V-Halbleiter (GaAs, InP, GaN) weiter. Anlagen können einem interessierten Fachpublikum auf diese Weise vor Ort demonstriert werden. SENTECH beauftragt aber auch Technologie-Transferleistungen, die direkt in die technologische Entwicklung bei SENTECH einfließen. Sie bilden die Grundlage für zukünftige Innovationen auf dem Gebiet der Plasmaätz- und Abscheidetechnik.

Eng ist auch die Zusammenarbeit mit dem Berliner Unternehmen LayTec. Gemeinsam mit dem FBH hat LayTec den in-situ Krümmungssensor EpiCurve erprobt und weiterentwickelt. Auch die EpiNet-Software wurde am FBH mit Messungen einem Praxistest unterzogen. Damit kann die Waferkrümmung während der Epitaxie elektronischer und optoelektronischer Bauelemente unmittelbar am Ort und sehr präzise überwacht werden. Wafer für Galliumnitrid-basierte Bauelemente, z.B. für Leuchtdioden (LEDs), sind materialbedingt oft stark gewölbt. Durch gezielte Steuerung der Waferkrümmung während des Epitaxieprozesses kann die Verbiegung minimiert werden. In Tests am FBH konnte die Waferkrümmung auch während des Plasmaätzens in-situ verfolgt werden und wichtige Schlussfolgerungen für die Prozessführung gezogen werden. Im Ergebnis lassen sich damit Qualität und Ausbeute der Bauelemente deutlich steigern.

Administration – efficiently organized and increasingly digitalized

The excellent research at FBH is supported by smooth administrative processes. Like every publicly funded research institute, FBH is subject to the strict budgetary and procurement directives of its funders, and accordingly those of the State of Berlin and the Federal Republic of Germany. As regulations have tightened over recent years, administrative staff has had to adapt to increasingly complex requirements. With their specialist knowledge, of procurement law for example, the team supports FBH's nearly 300 employees – disburdening them so that they can concentrate on their core duties.

Nine employees at FBH are directly responsible for finances, controlling, human resources, purchasing, sales, customs, and shipping and receiving. These areas have been undergoing radical changes for a number of years now and will continue evolving into the near future. A generation change has already begun in administration, for example: certain employees who were present at the founding of FBH and its structures are now entering retirement. Established workflows and forms are fundamentally changing as business processes in administration are being digitalized – with increasing time pressure given that new software always has to be introduced alongside ongoing business operations.

The admin staff at FBH is also the liaison to the joint administration of the Forschungsverbund Berlin, where a further 80 employees are responsible for the eight institutes of the Forschungsverbund, supporting them in particular in the areas of human resources, finances, procurement, and building and property management. Again, the rule is to organize the processes smoothly without temporal delays.

FBH's administration team.
Das Verwaltungs-Team am FBH.

A constant eye on the figures

The largest department of FBH's administration is financing. In order to standardize the complex finance management processes, project management software PROMAN was introduced in 2016. This facilitates the management of external funding for nearly 150 simultaneously running research projects, all funded by different sources. This includes public funding, e.g. from the Federal Ministry of Education and Research (BMBF), the European Union (EU) and the German Research Foundation (DFG), as well as industrial contracts. The largest "project" is the basic budget provided by the German federal and state (Länder) governments, of more than 13 million Euros (2016).

With efficient controlling, an FBH employee determines the prices for research services and development orders. Orders for customers from research and industry can be calculated realistically based on actual costs. These figures are also the basis for determining the institute's overheads, which can thus be certified and presented transparently to the funding authorities each year.

Procurement: all done electronically within strict guidelines

Procurement of goods and services is definitely one area that is becoming more demanding. There are well over 1,500 procurement transactions per year, all increasingly complex and time-consuming since not only verification of the origin of raw materials, but also proof of the suppliers' expertise, performance and reliability have to be requested and controlled before every acquisition. In turn, customers also demand details and transparency, for example, regarding the origin of materials. Migration to electronic systems is further changing the processes of customers and suppliers, who need documents to match their own specifications to continue processing them at their end.

Not only the customers are migrating their systems. In future, procurement at all eight institutes of the Forschungsverbund will be done electronically using procurement software compliant with Germany's procurement and contract procedures for public supplies and services (Vergabe- und Vertragsordnung für Leistungen, VOL). Thorough process analyses were conducted in 2015 in preparation for this. Based on their results, in 2016, the Forschungsverbund introduced Administration Intelligence AG's purchasing platform and procurement software, Vergabemanager, through which all procurement transactions will be made starting from 2018 – legally watertight and exclusively electronically. Via this electronic platform, the purchases of the entire Forschungsverbund will be analyzed more precisely and, in future, better terms negotiated with the suppliers. Electronic invoice processing was introduced and thus the process fully migrated to electronic entry and processing already at the beginning of 2017.

Further services behind the scenes of research and development

Service areas such as shipping and receiving, human resources, and the organization and invoicing of business trips are already handled directly within FBH. More than 3,000 consignments are shipped or received by the institute each year, including international customs clearance. These processes must be organized without delays, for example when it comes to urgently needed process gases or wafer materials procured from abroad, which must be available on time for the research projects in accordance with the regulations.

FBH directly handles about 380 business trips a year to conferences, project meetings and customer premises, plus an average of around 250 personnel service processes, and the sale of services. In 2016, sales sent out more than 160 offers, handled nearly 220 orders, and wrote more than 350 invoices. This section was also completely digitalized in the period from 2015 to 2016 – a necessary and wise course of action, even if it did briefly increase the workload and necessitate a restructuring of workflows.

Digital archiving of the purchasing processes began in 2015, and sales came next in 2016. In future, an association-wide solution will be needed with interfaces to all existing and future electronic administration products. In any event, the staff has marvelously handled all changes introduced so far and, with the past and present modernization and administration projects, the FBH and the Forschungsverbund feel well equipped for the future. This includes, for example, the imminent challenges posed by the "Research Fab Microelectronics Germany". The BMBF is funding this ambitious concept of a multi-location research factory for micro- and nanoelectronics with up to 400 million Euros in total, more than 34 million of which will go to the FBH over the next 3.5 years.

Verwaltung – effizient organisiert und zunehmend digitalisiert

Die exzellente Forschung des FBH wird unterstützt durch reibungslose Verwaltungsabläufe. Wie jedes öffentlich geförderte Forschungsinstitut unterliegt das FBH dabei den besonderen Haushalts- und Vergaberichtlinien der Zuwendungsgeber, und somit jenen des Landes Berlin und des Bundes. Da diese Regularien in den letzten Jahren verschärft wurden, werden auch die Anforderungen an die Verwaltungsmitarbeiterinnen und -mitarbeiter immer komplexer. Mit ihrem Spezialwissen, etwa im Vergaberecht, unterstützen sie die insgesamt fast 300 Kolleginnen und Kollegen am FBH – und entlasten diese, damit sie sich auf ihre Kernaufgaben konzentrieren können.

Neun Mitarbeiterinnen und Mitarbeiter sind direkt am FBH für Finanzen, Controlling, Personal, Einkauf, Verkauf, Zoll, Warenannahme und -versand zuständig. Das sind zugleich Bereiche, in denen sich seit einigen Jahren große Veränderungen vollziehen, die sich in den nächsten Jahren fortsetzen werden. So hat bereits ein Generationswechsel in der Verwaltung begonnen: Mitarbeiterinnen, die teilweise seit dem Aufbau des FBH und seiner Strukturen dabei waren, gehen in Rente. Parallel verändern sich etablierte Arbeitsabläufe und Formulare grundlegend durch die Digitalisierung der Geschäftsprozesse in der Verwaltung – mit steigender zeitlicher Belastung, da die Einführung der neuen Software immer parallel zum laufenden Betrieb durchgeführt wird.

Die Kolleginnen und Kollegen am FBH sind zugleich die Schnittstelle zur Gemeinsamen Verwaltung im Forschungsverbund Berlin. Dort sind weitere 80 Mitarbeiterinnen und Mitarbeiter für die insgesamt acht Forschungsverbund-Institute zuständig und unterstützen diese insbesondere in den Bereichen Personal, Finanzen und Beschaffungswesen sowie Bau- und Gebäudemanagement. Auch hier gilt es, die Abläufe reibungslos und ohne zeitlichen Verzug zu organisieren.

Die Zahlen stets im Blick

Der größte Bereich der Institutsverwaltung am FBH ist der Bereich Finanzen. Um die administrative Verwaltung der komplexen Projekte zu standardisieren wurde 2016 die Projektmanagement-Software PROMAN eingeführt. Das erleichtert die Verwaltung der Drittmittel aus knapp 150 parallel laufenden Forschungsvorhaben, die aus unterschiedlichen Quellen finanziert werden. Dazu zählen sowohl öffentliche Förderungen wie etwa aus dem Bundesministerium für Bildung und Forschung (BMBF), der Europäischen Union (EU) und der Deutschen Forschungsgemeinschaft (DFG), als auch Aufträge aus der Industrie. Das größte „Projekt" ist der von Bund und Ländern zur Verfügung gestellte Grundhaushalt mit mehr als 13 Millionen Euro (2016).

Mit einem effizienten Controlling ermittelt eine Mitarbeiterin am FBH die Preise für Forschungsdienstleistungen und Entwicklungsaufträge. Anhand der tatsächlichen Kosten können die Aufträge für Kunden aus Forschung und Industrie realistisch kalkuliert werden. Diese Zahlen bilden auch die Basis beispielsweise für die Berechnung der Institutsgemeinkosten, die hierdurch jährlich zertifiziert und den Zuwendungsgebern transparent nachgewiesen werden können.

Beschaffung: elektronisch und im Rahmen der strengen Vorgaben

Einen zunehmend anspruchsvoller werdenden Bereich stellt der Einkauf von Waren und Dienstleistungen dar. Die deutlich mehr als 1.500 Beschaffungsvorgänge pro Jahr werden immer aufwändiger und zeitintensiver, da nicht nur Nachweise zur Herkunft von Rohstoffen, sondern auch Belege zur Fachkunde, Leistungsfähigkeit und Zuverlässigkeit der Lieferanten vor jeder Beschaffung angefordert und kontrolliert werden müssen. Umgekehrt fordern die Kunden selbst Erklärungen und Transparenz, beispielsweise bei der Herkunft von Werkstoffen. Durch die Umstellung auf elektronische Systeme ändern sich zusätzlich die Abläufe bei Kunden und Lieferanten, die Unterlagen gemäß ihrer eigenen Vorgaben benötigen, um sie weiter verarbeiten zu können.

Nicht nur die Kunden stellen ihre Systeme um: Künftig soll in allen acht Forschungsverbund-Instituten die Beschaffung gemäß Vergabe- und Vertragsordnung für Leistungen (VOL) der Bundesrepublik Deutschland mittels einer Beschaffungssoftware elektronisch erfolgen. Hierzu wurden im Jahr 2015 Prozesse umfassend analysiert. Im Ergebnis wurden 2016 die Einkaufsplattform und der Vergabemanager der Administration Intelligence AG eingeführt, über die ab 2018 alle Beschaffungsvorgänge rechtssicher und ausschließlich elektronisch abgewickelt werden sollen. Durch die Nutzung der elektronischen Plattform können zukünftig die Einkäufe des gesamten Forschungsverbundes genauer analysiert und perspektivisch bessere Konditionen bei den Lieferanten erreicht werden.

Bereits Anfang 2017 wird die elektronische Rechnungsbearbeitung eingeführt und damit der Vorgang komplett auf elektronische Erfassung und Bearbeitung umgestellt.

Weitere Services hinter den Kulissen von Forschung und Entwicklung

Servicebereiche wie Warenannahme und -versand, Personalwesen sowie die Organisation und Abrechnung von Dienstreisen sind ebenfalls direkt am FBH angesiedelt. So werden mehr als 3.000 Sendungen jährlich vom Institut verschickt oder angenommen, inklusive internationaler Zollabfertigung. Diese Abläufe gilt es, ohne Zeitverzug zu organisieren, etwa wenn dringend benötigte Prozessgase oder Wafermaterial aus dem Ausland in Übereinstimmung mit den Regularien termingerecht für die Forschungsprojekte zur Verfügung stehen sollen.

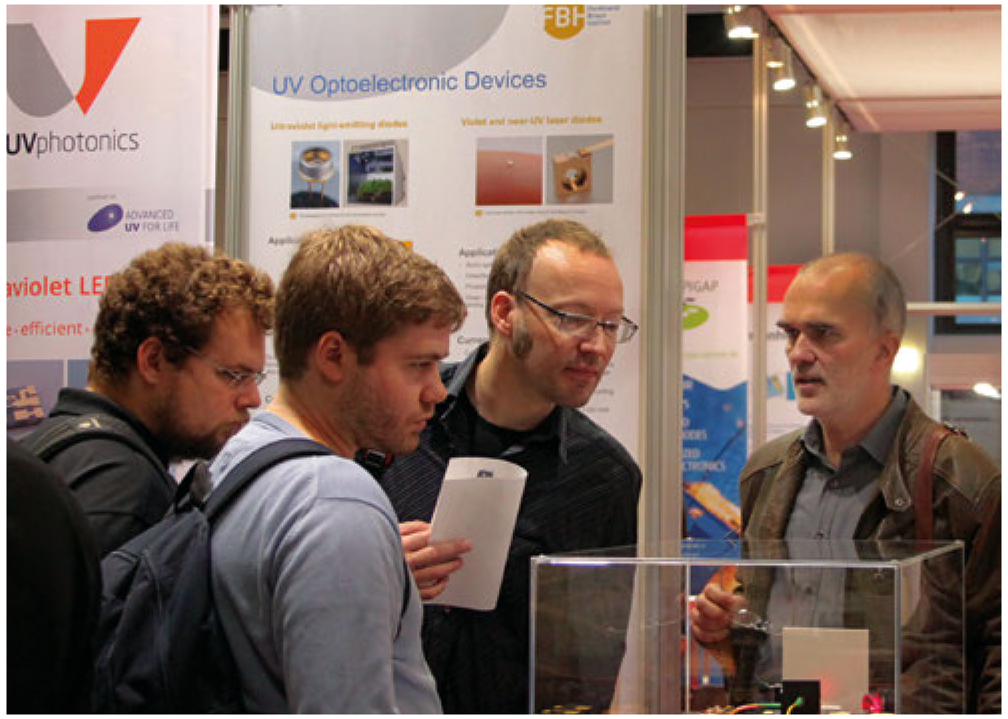
Auch die Abwicklung von jährlich etwa 380 Dienstreisen zu Konferenzen, Projekttreffen oder Kunden, die Personalsachbearbeitung mit durchschnittlich etwa 250 Personalvorgängen und der Verkauf von Leistungen sind direkt am FBH eingebunden. 2016 wurden im Verkauf mehr als 160 Angebote verschickt, knapp 220 Bestellungen abgewickelt und mehr als 350 Rechnungen erstellt. Dieser Bereich wurde in den Jahren 2015 und 2016 zudem komplett digitalisiert – ein notwendiger und sinnvoller Prozess, der allerdings kurzfristig die Arbeitsbelastung erhöht und für den Arbeitsabläufe umgestellt werden müssen.

2015 wurde auch mit der digitalen Archivierung der Einkaufsvorgänge begonnen, 2016 folgte der Verkauf. Perspektivisch wird eine verbundübergreifende Lösung benötigt mit Schnittstellen zu allen bereits eingeführten und noch kommenden elektronischen Verwaltungsprodukten. Die bereits durchgeführten Änderungen haben die Kolleginnen und Kollegen jedenfalls hervorragend gemeistert und durch die bereits abgeschlossenen beziehungsweise laufenden Projekte zur Verwaltungsmodernisierung fühlen sich das FBH und der Forschungsverbund gut gerüstet für die Zukunft. Dazu zählen beispielsweise die anstehenden Herausforderungen, die sich aus der „Forschungsfabrik Mikroelektronik Deutschland" ergeben. Das BMBF fördert dieses anspruchsvolle Konzept für eine standortübergreifende Forschungsfabrik für Mikro- und Nanoelektronik mit insgesamt bis zu 400 Millionen Euro, mehr als 34 Millionen davon fließen in den nächsten 3,5 Jahren an das FBH.

Events – for experts and the general public

For experts

In 2016, as always, FBH presented its research results at the key events of the scientific community, holding lectures at a total of 25 international conferences throughout the year. In February, FBH boosted its international visibility in the photonics research field, for example, at Photonics West in San Francisco, USA, with 19 expert presentations on diode lasers and UV LEDs – several of which were invited talks. With 20,000 participants and 1,250 exhibiters, this is the world's leading trade fair and conference for optics and photonics. FBH was also well represented in Berlin, at the congress-expo micro photonics in October. There, the institute presented its current developments together with the FBH-managed Zwanzig20 consortium *Advanced UV for Life*. The accompanying Career Lounge was organized by the Science Management Department. In this context, FBH also presented a number of intermediate results from its research project *AlFaClu*, which deals with the challenges facing photonics in light of demographic and technological change.



FBH booth at congress expo micro photonics 2016.
FBH-Messestand auf der Kongressmesse micro photonics 2016.

The results from FBH's research in the field of III-V electronics were presented at the relevant scientific events. The institute gave six presentations at the International Microwave Symposium in May, for example. In the scope of the invited workshop "Heterogeneous Integration of Silicon RFIC with III-Vs", FBH and the Leibniz institute IHP presented the jointly run heterointegrated InP-HBT/SiGe BiCMOS Foundry (SciFab). In October, FBH gave ten talks at the European Microwave Week on subjects including novel modulator concepts, THz signal sources, and digital amplifiers. One of the dominating topics of this particularly popular conference and expo, with 5,000 international visitors, was the next mobile telecommunications standard 5G. See also p. 24.

For junior academics
An example of FBH's contribution to the education of junior academics was its session "Radar Sensors and Laser Eyes for Autonomous Driving". Over five days, the Summer School 2016 organized by the Competence Network OptecBB offered diverse insights into intelligent sensor solutions used in the automotive industry – from research and current applications to future solutions.

For the interested general public
In 2016, FBH once again opened its laboratories to a broad general public. In April, around twenty 5th to 10th grade school students visited FBH and learned about careers in the fields of microtechnology, research and development. Trainees and researchers guided the pupils through the institute, explained how lasers work, and showed what they are currently working on in many practical experiments. Nearly 650 interested visitors also came to see FBH on the Long Night of Sciences for its diverse program of laboratory and cleanroom tours and hands-on experiments.

Microtechnologist explaining to visitors during the Long Night of Sciences how microchips work.
Mikrotechnologin erklärt Besucherinnen auf der Langen Nacht der Wissenschaften, wie Mikrochips funktionieren.

For friends of the institute
In April, FBH held a colloquium to celebrate the Director's 60th birthday and, on the same occasion, inaugurated the new extension building. Under the direction of Günther Tränkle, the Ferdinand-Braun-Institut has grown enormously, distinguished itself scientifically and maintained its high international visibility over the past 20 years. The speakers from research and industry honored his services to the development of III-V compound semiconductors and technology transfer. Welcoming speeches were given by Senator Cornelia Yzer (Senate Department for Economics, Technology and Research), Ministerial Director Dietrich Nelle (BMBF) and Matthias Kleiner (President of the Leibniz Association). The new building was erected in the period from 2013 to 2015 and occupied from the end of 2015, offering an additional 1,800 square meters of office and laboratory space.

Veranstaltungen – für Experten und ein breites Publikum

Für das Fachpublikum
2016 hat das FBH erneut seine Forschungsergebnisse auf den zentralen Branchentreffs vorgestellt und war 2016 auf insgesamt 25 internationalen Fachkonferenzen mit eigenen Beiträgen vertreten. Im Forschungsbereich Photonik hat das FBH seine internationale Sichtbarkeit im Februar unter anderem auf der Photonics West in San Francisco, USA, mit 19 Fachbeiträgen zu Diodenlasern und UV-Leuchtdioden erhöht – darunter mehrere eingeladene Vorträge. Mit 20.000 Teilnehmern und 1.250 Ausstellern ist dies die weltweit führenden Fachmesse und Konferenz für Optik und Photonik. Auch in Berlin war das FBH auf der Kongressmesse micro photonics im Oktober gut vertreten. Gemeinsam mit dem vom FBH geleiteten Zwanzig20-Konsortium *Advanced UV for Life* stellte das Institut dort eine Auswahl seiner aktuellen Entwicklungen vor. Die angeschlossene Career Lounge wurde vom Department Wissenschaftsmanagement organisiert. In diesem Zusammenhang präsentierte das FBH auch einige Zwischenergebnisse seines Forschungsprojektes *AlFaClu*, das sich mit den Herausforderungen für die Photonik vor dem Hintergrund des demografischen und technologischen Wandels beschäftigt.

Die Ergebnisse aus dem Forschungsbereich III/V-Elektronik des FBH wurden ebenfalls auf den relevanten Fachveranstaltungen vorgestellt. So etwa im Mai auf dem International Microwave Symposium, wo das Institut mit sechs Beiträgen vertreten war. Gemeinsam mit dem Leibniz-Institut IHP stellte das FBH dort im Rahmen des eingeladenen Workshops „Heterogeneous Integration of Silicon RFIC with III-V's" die gemeinsam betriebene heterointegrierte InP-HBT/SiGe-BiCMOS-Foundry (SciFab) vor. Im Oktober folgten zehn Vorträge des FBH auf der European Microwave Week, unter anderem zu neuartigen Modulatorkonzepten, THz-Signalquellen und digitalen Verstärkern. Eines der beherrschenden Themen der mit 5.000 internationalen Besuchern besonders stark frequentierten Konferenz mit begleitender Ausstellung war der nächste Mobilfunkstandard 5G, siehe auch S. 26.

Career lounge at micro photonics 2016, organized by FBH's Science Management Department – here during a school student event.
Die vom FBH-Wissenschaftsmanagement organisierte Career Lounge auf der micro photonics 2016 – hier bei einer Schülerveranstaltung.

Für den akademischen Nachwuchs
Das FBH beteiligte sich mit der Session „Radarsensoren und Laseraugen für autonomes Fahren" an der Weiterbildung des akademischen Nachwuchses. Die vom Kompetenznetz OptecBB organisierte Summer School 2016 bot fünf Tage lang vielfältige Einblicke in intelligente Sensoriklösungen, die im Automobilbereich zum Einsatz kommen – von der Forschung über aktuelle Anwendungen bis hin zu zukünftigen Lösungen.

Für die interessierte Öffentlichkeit
Auch 2016 öffnete das FBH seine Labore wieder für ein breites Publikum. Im April besuchten etwa zwanzig Schülerinnen der 5.-10. Klasse das FBH und informierten sich zu Berufen rund um Mikrotechnologie, Forschung und Entwicklung. Auszubildende, Wissenschaftlerinnen und Wissenschaftler führten die Schülerinnen durch das Institut, erklärten wie ein Laser funktioniert und zeigten an vielen praktischen Experimenten woran sie

täglich arbeiten. Knapp 650 Interessierte besuchten erneut das FBH zur Langen Nacht der Wissenschaften mit einem vielfältigen Programm von Labor- und Reinraumführungen bis hin zu Mitmachexperimenten.

Für die Freunde des Hauses

Im April lud das FBH zu einem Festkolloquium anlässlich des 60. Geburtstags seines Direktors und weihte zudem den neuen Erweiterungsbau ein. Das Ferdinand-Braun-Institut ist in den letzten 20 Jahren unter der Leitung von Günther Tränkle enorm gewachsen, hat sich wissenschaftlich profiliert und ist international weithin sichtbar. Die Festredner aus Forschung und Industrie würdigten seine Verdienste um die Entwicklung von III/V-Verbindungshalbleitern und den Technologietransfer. Grußworte sprachen die Senatorin Cornelia Yzer (Senatsverwaltung für Wirtschaft, Technologie und Forschung), Ministerialdirigent Dietrich Nelle (BMBF) und Matthias Kleiner (Präsident der Leibniz-Gemeinschaft). Der Neubau entstand in den Jahren 2013 bis 2015, wurde Ende 2015 bezogen und bietet zusätzliche 1.800 Quadratmeter Büro- und Laborflächen.

Prof. Karl Joachim Ebeling from Ulm University congratulates FBH director Günther Tränkle.
Prof. Karl Joachim Ebeling von der Universität Ulm gratuliert FBH-Direktor Günther Tränkle.

Personnel & Awards
Personalia & Auszeichnungen

LED start-up UVphotonics awarded Leibniz-Gründerpreis 2016

FBH's start-up company UVphotonics NT GmbH was awarded the Leibniz-Gründerpreis (Founder Award) 2016. The prize is endowed with 50,000 Euros and is intended to assist promising start-up companies with their market entry by means of external consulting. Altogether, eight start-up initiatives from Leibniz institutes have been nominated.

The founding team consists of three young FBH physicists and an experienced management expert. Neysha Lobo Ploch is a specialist for LED assembly and is responsible for marketing, sales, and quality management. Tim Kolbe is responsible for epitaxy and material development, and Jens Raß is in charge of LED processing and technology development. Walter Gibas, who most recently worked for a technology-oriented start-up, is responsible for the commercial management.

The founders of UVphotonics during the award ceremony with M. Kleiner, President of the Leibniz Association (left) and BMBF State Secretary G. Schütte (3rd from right).
Die Gründer von UVphotonics bei der Preisverleihung mit dem Präsidenten der Leibniz-Gemeinschaft M. Kleiner (links) und BMBF-Staatssekretär G. Schütte (3. v. rechts).

Berliner LED-Start-up UVphotonics erhält Leibniz-Gründerpreis 2016

Das Gründungsvorhaben UVphotonics NT GmbH aus dem FBH hat den Leibniz-Gründerpreis 2016 erhalten. Die mit 50.000 Euro dotierte Auszeichnung unterstützt erfolgversprechende Start-ups durch externe Beratung bei Markteintritt, Finanzierung und Marketing. Nominiert waren insgesamt acht Gründungsinitiativen aus Leibniz-Instituten.

Das Gründerteam besteht aus drei jungen Physikern des FBH und einem Betriebswirt: Neysha Lobo Ploch ist Expertin für den LED-Aufbau und zuständig für Marketing, Vertrieb und Qualitätsmanagement. Tim Kolbe ist für Epitaxie (Kristallwachstum) und Materialentwicklung verantwortlich. LED-Prozessierung und Technologieentwicklung liegen in der Zuständigkeit von Jens Raß. Die kaufmännische Leitung liegt bei dem Betriebswirt Walter Gibas, der zuletzt zehn Jahre für ein technologieorientiertes Start-up tätig war.

The thesis of Neysha Lobo Ploch received multiple awards.
Die Dissertation von Neysha Lobo Ploch wurde gleich mehrfach ausgezeichnet.

Chorafas Prize and Adlershof Dissertation Prize awarded to Neysha Lobo Ploch

Dr. Neysha Lobo Ploch was awarded the renowned Dimitri N. Chorafas Prize 2016 for her thesis entitled "Chip designs for high efficiency III-nitride based ultraviolet light emitting diodes with enhanced light extraction". This award is given for outstanding work in select fields in the engineering sciences, medicine, and the natural sciences. It rewards research characterized by its high potential for practical application and by the special significance attached to its repercussions. Ms. Lobo Ploch is co-founder of UVphotonics and additionally received the Adlershof Dissertation Prize for her thesis.

Chorafas-Preis und Dissertationspreis Adlershof an Neysha Lobo Ploch verliehen

Für ihre Dissertation „Chip designs for high efficiency III-nitride based ultraviolet light emitting diodes with enhanced light extraction" wurde Frau Dr. Neysha Lobo Ploch 2016 mit dem renommierten Dimitri N. Chorafas Preis ausgezeichnet. Der Preis wird seit 1992 an herausragende Promotionen aus ausgewählten Bereichen der Ingenieurwissenschaften, Medizin und Naturwissenschaften vergeben – mit besonderem Fokus auf hohem Anwendungs- und Zukunftspotenzial. Neysha Lobo Ploch ist Mitgründerin von UVphotonics und erhielt für ihre Promotionsarbeit außerdem den Dissertationspreis Adlershof.

Michael Kneissl

Michael Kneissl is a new IEEE Fellow

In January 2016, Prof. Dr. Michael Kneissl (Joint Lab GaN Optoelectronics) was selected to the join the distinguished circle of the IEEE Fellows for his contributions to the development of wide bandgap semiconductor laser diodes and ultraviolet LEDs. This fellowship signifies the highest grade of membership awarded by the renowned professional association for engineers in the field of electrical engineering and related disciplines.

Michael Kneissl ist IEEE Fellow

Im Januar 2016 wurde Prof. Dr. Michael Kneissl (Joint Lab GaN Optoelectronics) für seine Beiträge zur Entwicklung von Halbleiterlaserdioden großer Bandlücke und UV-LEDs in den illustren Kreis der IEEE-Fellows aufgenommen. Fellow bezeichnet die höchste Stufe der Mitgliedschaft der renommierten Berufsvereinigung für Ingenieure im Bereich der Elektrotechnik und verwandter Disziplinen.

Jan Schlegel awarded the Czochralski Prize

In November 2016, Jan Schlegel was honored for his master's thesis "preparation of waveguides and micro resonators in oxide" at Hochschule für Technik und Wirtschaft Berlin with the newly introduced Jan Czochralski Award. He wrote his thesis in the Process Technology Department at the Ferdinand-Braun-Institut, combining theoretical aspects of design with practical work for implementation in chips.

Jan Schlegel mit Czochralski-Preis ausgezeichnet

Für seine Masterarbeit „Herstellung von Mikroresonatoren in Siliziumdioxid" an der Hochschule für Technik und Wirtschaft Berlin wurde Jan Schlegel im November mit dem erstmalig verliehenen Jan-Czochralski-Preis ausgezeichnet. Die Arbeit wurde im Department Prozesstechnologie des Ferdinand-Braun-Instituts angefertigt und verbindet theoretische Aspekte des Designs mit praktischen Arbeiten zur Umsetzung in Chips.

Udo Pursche

Udo Pursche appointed professor

FBH scientist Udo Pursche has been appointed Professor for RF and Microwave Technology at Hochschule für Technik und Wirtschaft (HTW) Berlin. Effective from April 1, he is actively involved in the study programs "communications engineering" and "information technology/networked systems" in Faculty 1: Engineering – Energy and Information.

Udo Pursche auf Professur berufen

Zum 1. April wurde der FBH-Wissenschaftler Udo Pursche auf die Professur für Hochfrequenz- und Mikrowellentechnik an die Hochschule für Technik und Wirtschaft Berlin berufen. Ab sofort ist er dort im Fachbereich 1: Ingenieurwissenschaften – Energie und Information in den Studiengängen „Nachrichtentechnik" und „Informationstechnik/Vernetzte Systeme" tätig.

FBH publication among HPL's top downloads

The publication "High duty cycle, highly efficient fiber coupled 940-nm pump module for high-energy solid-state lasers" ranked among the top downloads of the High Power Laser Science and Engineering (HPL) Journal in the period from January to September 2016.

FBH-Publikation unter den Top Downloads bei HPL

Die Publikation „High duty cycle, highly efficient fiber coupled 940-nm pump module for high-energy solid-state lasers" gehörte im Zeitraum von Januar bis September 2016 zu den Top Downloads der Zeitschrift High Power Laser Science and Engineering (HPL).

Journal of Crystal Growth honors FBH publication

The publication "High quality AlGaN grown on ELO AlN/sapphire templates", published in 2013, had been cited 30 times by June 2016. The authors were accordingly distinguished with the "highly cited research" award.

Journal of Crystal Growth zeichnet FBH-Publikation aus

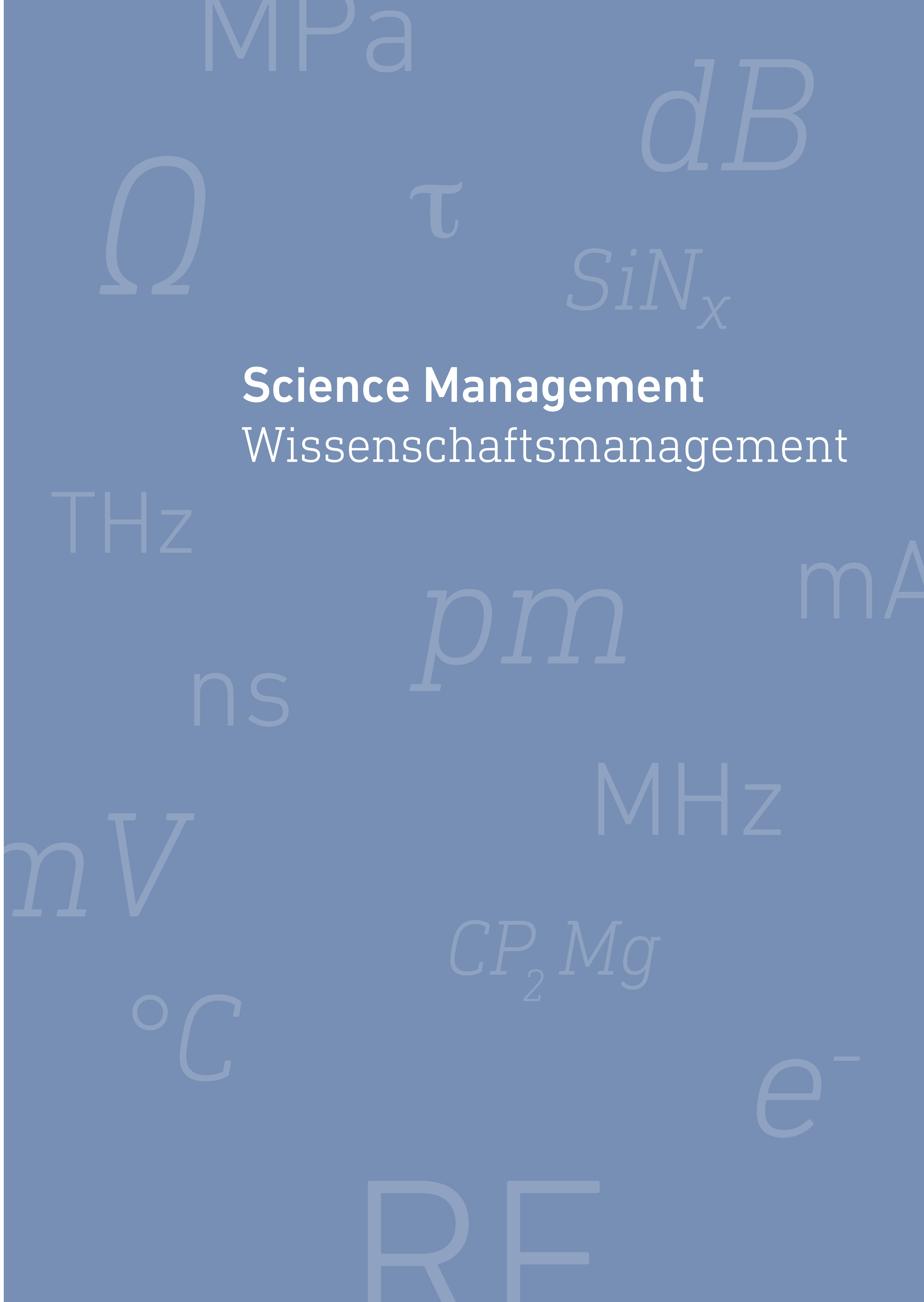
Die 2013 veröffentlichte Publikation „High quality AlGaN grown on ELO AlN/sapphire templates" ist bis Juni 2016 30-mal zitiert woren. Dafür wurden die Autoren mit dem Zertifikat für „highly cited research" ausgezeichnet.

Outstanding Reviewer Awards

Hans Wenzel and Carsten Netzel were acknowledged as outstanding reviewers for the journal "Semiconductor Science and Technology", which publishes cutting-edge research on the physical properties of semiconductors and their applications.

Outstanding Reviewer Awards

Hans Wenzel und Carsten Netzel wurden für ihre hervorragenden Leistungen als Gutachter für „Semiconductor Science and Technology" ausgezeichnet. Das Journal publiziert richtungsweisende Forschung zu physikalischen Eigenschaften und Anwendungen von Halbleitern.



Science Management
Wissenschaftsmanagement

Science Management Wissenschaftsmanagement

Science Management – supporting R&D

The Science Management Department provides services that keep the institute's organizational processes running. Its IT support group, for example, is taking care of computer infrastructure and data security, among others. The institute's administration, which is also assigned to the department, is the interface to the joint administration of the Forschungsverbund, thus ensuring smooth overall processes from acquisitions to business trips (see also p. 40).

Moreover, the Science Management Departments supports scientists with their projects and R&D cooperation – up to international networks and collaborative research projects. The interdisciplinary team is also involved in major industrial and research projects. It takes over administrative and non-scientific tasks that result from the application of complex collaborative research projects as well as from the coordination, development, and management of such project networks.

A focus of the department is on the coordination of the Twenty20 consortium *Advanced UV for Life*, meanwhile comprising 38 partners. The consortium researches and develops UV LED technology along the complete value chain – from the crystal to the system application used, for example, for the detection of germs. In 2016, five projects were completed and 13 new got off the ground; altogether 21 projects are handled in parallel. The institute is involved in eight of them, partly in a leading role. For research activities, the consortium has up to 45 million Euros at its disposal until 2021.

The Prototype Engineering Lab created in 2014 is also organizationally assigned to the Science Management Department. The lab constructs modules up to prototypes in order to test them in the respective application field. The four-headed team is making sure that FBH's research results are transferred into applications even faster. With this systematic apparatus engineering, components and modules of the institute are integrated into systems and demonstrated operationally. In 2016, the team took up quarters in the new FBH building with its own prototype development lab.

Further emphasis is put on education and training as well as securing skilled personnel. Activities especially target young people to promote careers in natural sciences and technology as well as to sustainably secure qualified employees. Two new projects started in 2016: *HAI* and *beMINT*. *HAI – Hightech-Ausbildung in Berlin-Brandenburg* (high-tech training in Berlin-Brandenburg) assists companies with entering into vocational training and supports the implementation process, also helping with filling training positions. *HAI* is already the third project funded within the Jobstarter program that is carried out at FBH. *beMINT* is funded by the Berlin economy via IHK Berlin and informs young people about training positions in the high-tech area. Both projects are handled under the roof of the Education Network High Technology Berlin (ANH Berlin), which is coordinated by the FBH since 2007.

Wissenschaftsmanagement – Unterstützung für die Forschung

Das Department Wissenschaftsmanagement unterstützt mit seinen Services die organisatorischen Abläufe am Institut. So kümmert sich die Abteilung mit ihrer EDV-Gruppe unter anderem um Rechnerinfrastruktur und Datensicherheit. Mit der Institutsverwaltung bildet sie die Schnittstelle zur Gemeinsamen Verwaltung des Forschungsverbunds und sorgt für reibungslose Abläufe, von der Beschaffung bis hin zu Dienstreisen (siehe auch S. 42).

Darüber hinaus unterstützt die Abteilung die Wissenschaftlerinnen und Wissenschaftler bei Projekten und F&E-Kooperationen – bis hin zu internationalen Netzwerken und Verbund-forschungsvorhaben. Auch in größere Industrieprojekte und Fördervorhaben ist das interdisziplinär aufgestellte Team eingebunden. Es übernimmt administrative und nichtwissenschaftliche Arbeiten, die bei der Beantragung komplexer Verbundvorhaben, der Koordination, Entwicklung und dem Management derartiger Projektverbünde anfallen.

Ein Schwerpunkt im Department ist die Koordination des Zwanzig20-Konsortiums *Advanced UV for Life*. Das auf mittlerweile 38 Partner angewachsene Konsortium erforscht und entwickelt die UV-LED-Technologie entlang der kompletten Wertschöpfungskette – vom Kristall bis zur Anwendung in Geräten wie etwa zur Detektion von Keimen. 2016 konnten fünf Vorhaben abgeschlossen werden und 13 neue Projekte starteten; insgesamt laufen damit 21 Projekte parallel. Das Institut ist in acht dieser Vorhaben teils federführend eingebunden. Für die Forschungsarbeiten stehen dem Konsortium bis 2021 insgesamt bis zu 45 Millionen Euro zur Verfügung.

Auch das 2014 geschaffene EntwicklungsZentrum ist organisatorisch dem Wissenschaftsmanagement zugeordnet. Es baut Module bis hin zu Prototypen, die so im jeweiligen Anwendungsfeld getestet werden können. Das vierköpfige Team sorgt dafür, dass Forschungsergebnisse des Instituts noch schneller in Applikationen überführt werden. Mit dem systematisierten Gerätebau werden die Komponenten und Module des FBH in Systeme integriert und einsatzfähig demonstriert. 2016 konnte das Team ein eigenes Labor für die Prototypentwicklung im Neubau des FBH beziehen.

Ein weiterer Schwerpunkt liegt bei der Aus- und Weiterbildung sowie der Fachkräftesicherung. Dabei soll insbesondere geeigneter Nachwuchs für den naturwissenschaftlich-technischen Bereich geworben und Personal nachhaltig gesichert werden. 2016 starteten zwei neue Vorhaben: *HAI* und *beMINT*. *HAI – Hightech-Ausbildung in Berlin-Brandenburg* unterstützt Betriebe beim Einstieg in die gewerblich-technische Ausbildung und bei der Umsetzung. Es hilft zudem bei der Besetzung von Ausbildungsplätzen. *HAI* ist bereits das dritte Projekt im Jobstarter-Förderkontext, das am FBH durchgeführt wird. *beMINT* wird von der Berliner Wirtschaft über die IHK Berlin gefördert und informiert Jugendliche gezielt über Ausbildungsberufe im Hochtechnologiebereich. Beide Vorhaben laufen unter dem Dach des Aus- und Weiterbildungsnetzwerks ANH Berlin, das seit 2007 vom FBH koordiniert wird.

Advanced UV for Life – bringing UV LED technologies into application

ADVANCED
UV FOR LIFE

Since the beginning of 2014, the *Advanced UV for Life* consortium managed by FBH addresses the development and application of UV LEDs. Within the close cooperation between research institutions and industry, the partners collaborate on application-specific research issues. In this way, they develop customized UV LED technologies of high social relevance. The consortium is funded with up to 45 million Euros until 2021 by the German Federal Ministry of Education and Research within the "Twenty20 – Partnership for Innovation" program.

The coordination office of *Advanced UV for Life* is managed by FBH's Science Management Department, ensuring the smooth flow of information within the consortium. The office is also taking care of exploitation and transfer of research results achieved within the network. Together with customized support for the currently 38 partners, the coordination office provides the basis for a successful and sustainable collaboration. Particular attention is paid to the interfaces between the 29 R&D projects in order to successfully handle the complex projects and to effectively implement the consortium strategy.

Furthermore, joint public relation activities have gained relevance, thus enhancing the visibility of *Advanced UV for Life* and increasing acceptance of the innovative R&D results. The consortium exhibited a selection of current developments at the international "micro photonics" trade show in Berlin from 11 - 13 October 2016. At this congress expo, FBH presented the range of products and services provided by the consortium along the whole value chain together with the consortium partners UVphotonics NT GmbH, sglux SolGel Technologies GmbH, OSA Opto Light GmbH, and micro resist technology GmbH. Latest UV LED and UV photodiode developments along with module construction and manifold UV LED-based applications including production and water treatment were exhibited.

Consortium partners appreciate the dedicated commitment of the coordination office, lastly reflected by a joint resolution approved in November 2016. The decision includes a co-financing agreement, sharing the costs for coordination and management tasks provided by the FBH team. As a result, financing the office is ensured until the end of the Twenty20 project period.

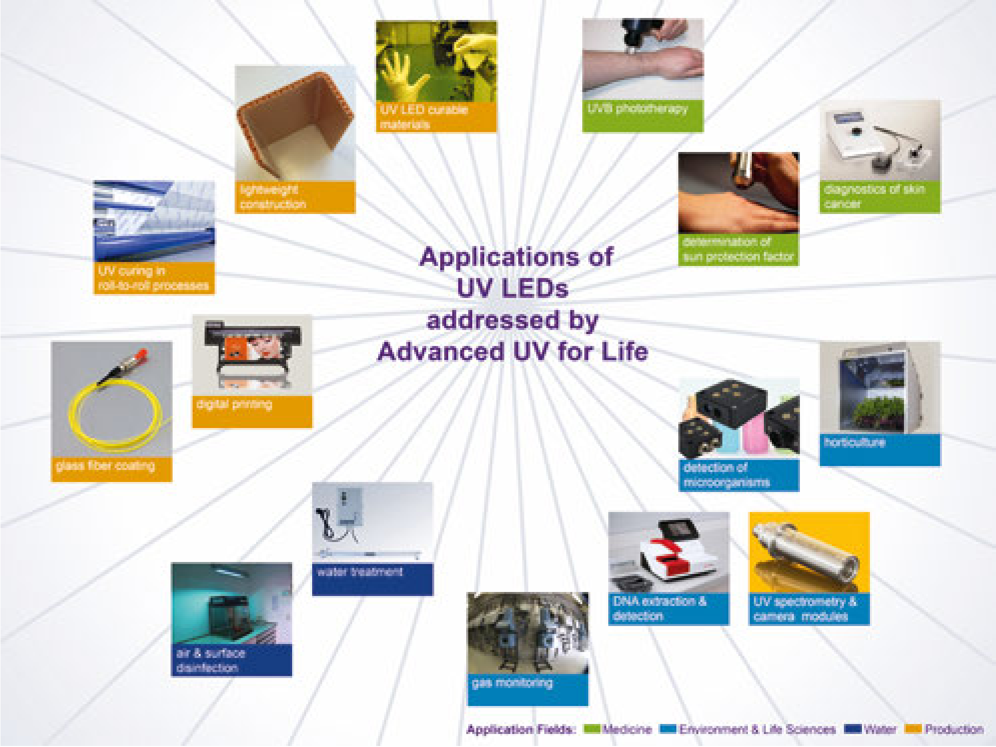
FBH and *Advanced UV for Life* represented the consortium jointly at the congress expo "micro photonics" in Berlin.
Das FBH und *Advanced UV for Life* präsentierten sich auf der Kongressmesse „micro photonics" in Berlin.

Advanced UV for Life – bringt UV-LED-Technologien in die Anwendung

Seit Anfang 2014 widmet sich das vom FBH geleitete Konsortium *Advanced UV for Life* der Entwicklung und Anwendung von UV-LEDs. Wissenschaft und Wirtschaft kooperieren hierbei eng und bearbeiten gemeinsam anwendungsspezifische Forschungsfragen. Die Partner entwickeln so maßgeschneiderte UV-LED-Technologien mit hoher gesellschaftlicher Relevanz. Im Rahmen des Programms „Zwanzig20 – Partnerschaft für Innovation" wird das Konsortium mit bis zu 45 Millionen Euro bis nunmehr Ende 2021 vom BMBF gefördert.

Die Koordinationsstelle von *Advanced UV for Life* ist im Department Wissenschaftsmanagement des FBH angesiedelt. Sie sorgt für den reibungslosen Informationsfluss zwischen den Partnern und steuert die Verwertung und den Transfer der erzielten Ergebnisse. In Verbindung mit maßgeschneiderten Unterstützungsleistungen für die aktuell 38 Partner legt die Koordinationsstelle die Grundlagen für eine erfolgreiche und nachhaltige Kooperation. Besonderes Augenmerk gilt dabei den Schnittstellen zwischen den mittlerweile 29 F&E-Vorhaben des Konsortiums. Nur so lassen sich die komplexen Projekte erfolgreich bearbeiten und die Konsortialstrategie wirksam umsetzen.

Darüber hinaus gewinnt die gemeinsame Öffentlichkeitsarbeit an Bedeutung. Sie verbessert die Sichtbarkeit des Konsortiums und erhöht die Akzeptanz für die innovativen F&E-Ergebnisse. Eine Auswahl seiner aktuellen Entwicklungen stellte *Advanced UV for Life* auf der Kongressmesse „micro photonics" in Berlin vom 11. bis 13. Oktober 2016 vor. Gemeinsam mit den Konsortialpartnern UVphotonics NT GmbH, sglux SolGel Technologies GmbH, OSA Opto Light GmbH und micro resist technology GmbH präsentierte das FBH das Leistungsspektrum des Konsortiums entlang der kompletten Wertschöpfungskette – angefangen bei den neuesten Entwicklungen von UV-LEDs, UV-Fotodetektoren über den



Modulbau bis hin zu den vielfältigen Anwendungen der UV-LED-Technologie in den Bereichen Produktion und Wasserbehandlung.

Die Partner des Konsortiums schätzen dieses Engagement der Koordinationsstelle, wie auch der gemeinsame Beschluss vom November 2016 zeigt. Darin wurde eine Umlageregelung vereinbart, mit der die Koordinations- und Managementaufgaben beim FBH finanziert werden und die Arbeit der Koordinationsstelle verstetigt wird. Deren Finanzierung ist somit bis zum Ende der Programmlaufzeit von Zwanzig20 gewährleistet.

Prototype Engineering – successful transfer of FBH research results

The Ferdinand-Braun-Institute is transferring excellent research results rapidly into market-oriented products, services, and processes. To expand its scientific activities toward systematic device engineering, FBH has started the Prototype Engineering Lab in 2014. By advancing research modules in the direction of industry-ready, user-friendly prototypes, the institute expands its expertise. It therefore accelerates research and development processes and strengthens business relations sustainably.

Modules for plant growth and water disinfection

Already in 2015, the Prototype Engineering Lab has developed a UV-B LED module for plant growth lighting together with the Joint Lab GaN Optoelectronics. This module allows irradiation of a defined area with UV-B light of a specific wavelength and is used by a research partner. The field-tested module was also a trigger for the new joint research project *SEcondaRy UV* of the Joint Lab GaN Optoelectronics. In 2016, another irradiation UV LED module with a different wavelength was built, allowing the research partner to test and compare the influence of two differing wavelengths on the biosynthesis of specific secondary plant compounds. To vary this investigation, a third irradiation module is scheduled to be implemented in 2017. Demonstrating UV-B LEDs in specific applications extends the scope of research activities at FBH, additionally leading to follow-up projects.

For water disinfection purposes, the Prototype Engineering Lab has developed an irradiation module with 262 nm LEDs (Fig. 1) aiming to replace conventional low-pressure mercury vapor lamps. UV LEDs score with higher lifetimes and are maintenance-free. Since they do not require toxic chemicals like mercury they are environmentally friendly in addition – mercury lamps need to be disposed safely after a few 1,000 hours operation. Wavelength and emission characteristics of LEDs can also be adjusted specifically to fit the desired application. The geometry was adjusted to conventional flow-through water disinfection reactors used, for example, for treatment of drinking or process water. The FBH setup is modularly expandable and can thus be adapted to various reactor sizes. Two LEDs form an assembly group with constant current supply (max. 100 mA per LED) and temperature termination for security reasons. Heat is dissipated via heat pipe with attached fan.

Advancing research models to operational devices

Another focus of the team is on effectively collaborating with the research labs and departments in house. One example for the good teamwork is the digitalization of electronic control units of several photonic and III-V electronic research modules. The engineers of the Prototype Engineering Lab have not only extended their knowledge in electronic engineering and programming of FPGA components, but have also developed into in house experts for 3D design software Solid Edge ST8.

All devices are mounted and tested in a newly established laboratory (Fig. 2), comprising common electronic instruments as well as RF measurement and thermal management measurement equipment. In future, the lab also plans to expand its activities in the field of Raman spectroscopy together with the Laser Sensors Lab. A confocal Raman microscope is now part of the infrastructure, enabling to analyze the composition of samples spatially resolved within micron range. Raman microscopy has applications in material sciences, geology/mineralogy, pharmacy, gemology, food and agricultural technology, environmental engineering, process chemistry, medicine and forensic science.

Fig. 1. Rod-shaped UV-C irradiation module for water disinfection (top: water supply, left: cooling).
Abb. 1. Stabmodul zur Wasserdesinfektion – Demonstrator mit UVC-LEDs (Wasseranschlüsse oben, Kühlung links).

The institute is establishing its Prototype Engineering Lab with the help of the BMBF-funded *Veriplan* project (03/2014 – 02/2017). To further promote successful exploitation of FBH's research results, the project *InnoMatch* (Innovationswerkstatt Leibniz – matching supply and demand between science and industry) has started in October 2016. R&D results shall be optimized to fit the needs of small- and medium-sized companies. By matching supply and the actual demand, the lab can develop models and small-scale series tailored to suit their requirements. Moreover, the institute expands its marketing, sales and collaboration management activities to access new application fields.

EntwicklungsZentrum – Forschungsergebnisse aus dem FBH erfolgreich verwerten

Exzellente Forschungsergebnisse überführt das Ferdinand-Braun-Institut zügig in marktorientierte Produkte, Verfahren und Dienstleistungen. Um seine wissenschaftlichen Aktivitäten mit einem systematisierten Gerätebau zu ergänzen, hat das FBH 2014 das EntwicklungsZentrum geschaffen. Das Institut erweitert so seine Kompetenz beim technischen Aufbau von Forschungsmodulen zu industrietauglichen, nutzerfreundlichen Prototypen. Es beschleunigt damit Entwicklungsprozesse und stärkt langfristig seine Beziehungen zu Unternehmen.

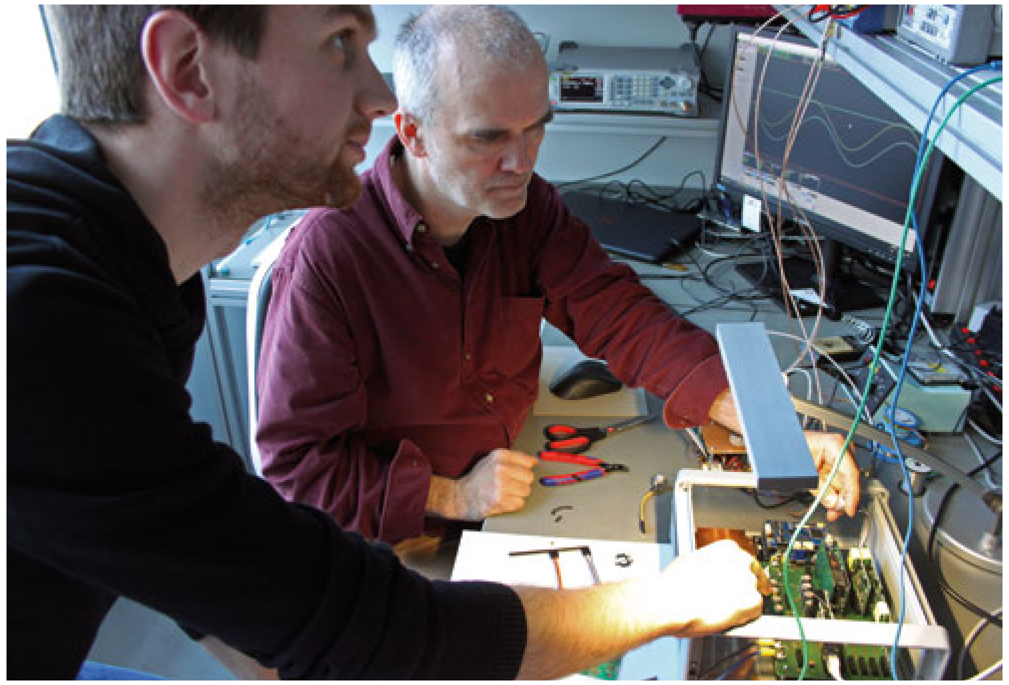


Fig. 2. Colleagues of the Prototype Engineering Lab assembling a prototype in their laboratory.
Abb. 2. Kollegen des EntwicklungsZentrums im Labor zum Aufbau von Prototypen.

Module für Pflanzenzucht und Wasserdesinfektion
Bereits im Jahr 2015 wurde, gemeinsam mit dem Joint Lab GaN Optoelectronics, ein Modul zur Pflanzenzucht mit UV-B-LEDs für einen Forschungspartner entwickelt. Das Gerät ermöglicht die flächige Bestrahlung von Pflanzen mit UV-B-Strahlung spezifischer Wellenlänge. Das erprobte Modul war ein Baustein für das neue Verbundvorhaben *SEcondaRy UV* des Joint Labs GaN Optoelectronics. 2016 wurde im EntwicklungsZentrum ein weiteres Bestrahlungsmodul mit UV-LEDs anderer Wellenlänge realisiert. Damit kann der Forschungspartner den Einfluss der zwei verschiedenen Wellenlängen auf die Biosynthese spezieller Pflanzenwirkstoffe untersuchen und vergleichen. Um die Untersuchung weiter zu variieren, soll in 2017 ein drittes Bestrahlungsmodul umgesetzt werden. Die Demonstration seiner UV-B-LEDs im speziellen Anwendungsfeld des Pflanzenwachstums eröffnet für das FBH zugleich weiterführende Forschungsarbeiten.

Für die Wasserdesinfektion wurde ein Stabmodul mit 262 nm LEDs aus eigener Herstellung entwickelt (Abb. 1), das bislang genutzte Niederdruck-Quecksilberdampflampen ersetzen soll. UV-LEDs können mit ihrer längeren Lebensdauer und Wartungsfreiheit punkten. Da sie ohne giftige Chemikalien wie Quecksilber auskommen, sind sie zugleich umweltfreundlich – Quecksilberlampen müssen nach wenigen 1.000 Stunden Betrieb sicher entsorgt werden. Bei den LEDs lassen sich zudem die Wellenlänge und Abstrahleigenschaften gezielt verändern und somit auf die gewünschte Anwendung optimieren. Die Geometrie wurde an herkömmliche Durchfluss-Wasserentkeimungs-Reaktoren – etwa zur Trink- und Prozesswasser-Aufbereitung – adaptiert. Der Aufbau ist modular erweiterbar und kann daher an verschiedene Reaktorgrößen angepasst werden. Zwei LEDs bilden je eine Baugruppe inklusive Versorgung mit Konstantstrom (max. 100 mA pro LED) und Temperaturabschaltung aus Sicherheitsgründen. Die entstehende Wärme wird über ein Wärmerohr mit angeschlossenem Ventilator abgeführt.

Weiterentwicklung von Forschungsmustern zu einsatzfähigen Geräten
Ein weiterer Fokus des EntwicklungsZentrums liegt auf der effektiven Zusammenarbeit mit den Forschungsbereichen des FBH. So wurde die Elektroniksteuerung von Modulen aus den Bereichen Photonik und III/V-Elektronik digitalisiert. Dazu hat sich das Team nicht nur in der Elektronikentwicklung und Programmierung von FPGA-Komponenten weitergebildet, sondern mittlerweile auch als Ansprechpartner für das 3D-Programm Solid Edge ST8 im Haus etabliert.

Montiert und getestet werden alle Geräte im neu eingerichteten Labor (Abb. 2), das neben der üblichen Ausrüstung eines Elektronik-Labors zusätzlich über einen Hochfrequenz- und einen Wärmemanagement-Messplatz verfügt. Auch Aufgaben zur Raman-Spektroskopie sollen künftig gemeinsam mit dem Laser Sensors Lab noch umfassender bearbeitet werden und zu passgenauen Prototypen führen. Dazu wurde ein konfokales Raman-Mikroskop beschafft, mit dem die Zusammensetzung von Proben ortsaufgelöst im Mikrometerbereich untersucht werden kann. Die Anwendungen der Raman-Mikroskopie liegen in den Bereichen Materialwissenschaften, Geologie/Mineralogie, Pharmazie, Edelsteinkunde, Lebensmittel- und Agrartechnik, Umwelttechnik, Prozesschemie, Medizin und Forensik.

Der Aufbau des EntwicklungsZentrums wird als Pilot-Projekt *Veriplan* vom BMBF drei Jahre lang (03/2014 – 02/2017) gefördert. Das Vorhaben *InnoMatch* (Innovationswerkstatt Leibniz – Matching von Angebot und Nachfrage zwischen Wissenschaft und Wirtschaft), das im Oktober 2016 gestartet ist, soll den Verwertungserfolg der eigenen Forschungsergebnisse weiter steigern. Die F&E-Ergebnisse sollen gezielt auf die Bedürfnisse von kleinen und mittelständischen Unternehmen optimiert werden. Durch dieses Matching zwischen Angebot und Nachfrage können bedarfsgerechte Forschungsmuster bis hin zu ersten Kleinstserien für neue Kooperationspartner aufgebaut werden. Darüber hinaus erweitert das FBH seine Aktivitäten zu Marketing, Vertrieb und Kooperationsmanagement, um FBH-Forschungsergebnissen neue Anwendungsfelder zu erschließen.

Outreach, education, and training in the photonics cluster

A small team within the Science Management Department coordinates training and education activities not only within the institute itself, but for the whole photonics cluster in the Berlin Brandenburg region. Main issues in 2016 were to develop appropriate measures to meet the needs of demographic and technological change:

Outreach
Many professions and training opportunities in high technology are still fairly unknown or even regarded as 'difficult' or 'unattractive'. Accordingly, the FBH team pursued a great variety of activities to inform young people – especially girls – about training opportunities and career prospects in science and technology. Apart from information days for schools and booths at training fairs, FBH offered photonics workshops for school students from 7th to 12th grade within the career lounge at "micro photonics" congress expo held in October 2016.

beMINT, a new project funded by the Berlin industry started at the end of October 2016. In close cooperation with the GenaU network of school laboratories and the vocational training center Lise Meitner (LMS), FBH addresses several aspects having an influence on young peoples' decision-making about their future careers. The *beMINT* activities combine practical laboratory experiments in STEM (science, technology, engineering, mathematics) with visits in companies and institutes along with first-hand information about training and working conditions. Additionally, the project helps both young people as well as companies to match vacancies and potential candidates for training.

PHABLABS 4.0, an EU-funded initiative through the horizon 2020 program, was launched in December 2016. It integrates photonics with the help of workshops and challenger projects into the rapidly expanding European Fab Labs, resulting in a larger and better skilled photonics workforce. The project consortium comprises eleven top-level photonics partners and 14 pilot fab labs spread over ten European countries. Photonics workshops are being developed to learn more about the enabling character of photonics and its various applications by creating some fascinating components, systems or pieces of art based on the unique properties of light.

Vocational and further training

Together with the new project *HAI* (high-tech training in Berlin-Brandenburg), FBH extends its services for small and medium-sized enterprises (SME) and research institutes. These efforts aim at raising the quality and attractiveness of vocational training in high technology and support companies and institutes in major training matters. From July 2016 onwards, the regional training network ANH Berlin received additional funding from the Federal Ministry of Education and Research (BMBF) to boost these activities.

AlFaClu is a BMBF-funded initiative of FBH and two universities from Hamburg that aims at meeting the challenges caused by demographic and technological changes. Within the project, adequate instruments and strategies for companies in the photonics cluster are being developed. Several concepts and tools have already been established along with a working group to join forces, share experiences, and to develop elaborate human resources for the future. As a highlight in 2016, *AlFaClu* presented selected intermediate results (i.e. concepts and tools for knowledge management and human resource development) within the career lounge at "micro photonics" congress expo and discussed their impact on the photonics cluster with representatives from industry, public administration and politics.

Nachwuchsgewinnung, Aus- und Weiterbildung im Cluster Optik

Ein kleines Team innerhalb des Wissenschaftsmanagements ist für Aus- und Weiterbildung zuständig. Es koordiniert in diesem Bereich nicht nur Aktivitäten für das Institut selbst, sondern für das gesamte Cluster Optik in der Region Berlin-Brandenburg. Das Hauptaugenmerk lag im Jahr 2016 auf Maßnahmen, die den Herausforderungen des demografischen und technologischen Wandels gerecht werden.

Trainee explaining training and career prospects in microsystems technology.
Azubi erläutert Ausbildungsmöglichkeiten und Berufschancen in der Mikrotechnologie.

Meeting of *PHABLABS 4.0* project partners in Brussels.
Treffen der *PHABLABS 4.0*-Projektpartner in Brüssel.

Nachwuchs

Viele Berufe und Ausbildungsmöglichkeiten in der Hochtechnologie sind nach wie vor relativ unbekannt, werden teils sogar als „zu kompliziert" oder „unattraktiv" angesehen. Dementsprechend arbeitet das FBH-Team aktiv daran, junge Menschen – vor allem Mädchen – über Ausbildungsmöglichkeiten und Karrierechancen in Wissenschaft und Technik zu informieren. Neben Informationstagen für Schulen und Infoständen auf Ausbildungsmessen bot das FBH im Oktober 2016 auch Photonik-Workshops an. Diese richteten sich im Rahmen der Karriere-Lounge auf der Kongress-Messe „micro photonics" an Schülerinnen und Schüler der 7. bis 12. Klasse.

beMINT ist ein neues Projekt, das von der Berliner Wirtschaft gefördert wird und Ende Oktober 2016 gestartet ist. In enger Zusammenarbeit mit dem Schülerlabor-Netzwerk GenaU und dem Oberstufenzentrum Lise Meitner (LMS) adressiert das Projekt zentrale Aspekte, die Einfluss auf die Karriereentscheidungen von Jugendlichen haben. Die *beMINT*-Aktivitäten (MINT – Mathematik, Naturwissenschaft, Informatik, Technik) kombinieren praktische Experimente in Laboren mit Besuchen bei Firmen und Instituten. Die Jugendlichen können sich dort direkt über Aufgabenbereiche und Arbeitsbedingungen informieren. Darüber hinaus bringt das Projekt junge Menschen mit Unternehmen zusammen, um passende Bewerber und freie Ausbildungsplätze besser zu vermitteln.

PHABLABS 4.0, eine EU-finanzierte Initiative im Rahmen des Programms Horizont 2020, ist im Dezember 2016 an den Start gegangen. Sie entwickelt Photonik-Workshops und Projekte für europäische Fab Labs. Damit leistet die Initiative ihren Betrag, mit dem qualifiziertes Personal für die Zukunft gesichert werden soll. Das Projektkonsortium umfasst elf hochkarätige Photonik-Partner und 14 Pilot-Fab-Labs in mehr als zehn europäischen Ländern. In diesem Zusammenhang werden Photonik-Workshops entwickelt, die unter anderem Technik und Kunst miteinander verbinden, um so mehr über die Photonik als eine der Schlüsseltechnologien des 21. Jahrhunderts zu erfahren.

Aus- und Weiterbildung

In Verbindung mit dem neuen Projekt *HAI* (Hightech-Ausbildung in Berlin-Brandenburg) erweitert das FBH seine Dienstleistungen für kleine und mittlere Unternehmen und Forschungsinstitute. Diese Aktivitäten zielen darauf ab, die Qualität und die Attraktivität der Berufsausbildung in der Hochtechnologie zu erhöhen und Unternehmen und Institute in allen Belangen rund um die Ausbildung zu unterstützen. Dafür erhält das regionale Aus- und Weiterbildungsnetzwerk ANH Berlin ab Juli 2016 zusätzliche Mittel des Bundesministeriums für Bildung und Forschung (BMBF).

State Secretary Reckers (Senate Department for Economics, Technology and Research) at the closure meeting of *AlFaClu* at "micro photonics".
Staatssekretär Reckers (Senatsverwaltung für Wirtschaft, Technologie und Forschung) beim Abschlusstreffen von *AlFaClu* auf der „micro photonics".

AlFaClu, eine BMBF-geförderte Initiative des FBH und zweier Universitäten aus Hamburg, zielt auf die Herausforderungen des demografischen und technologischen Wandels. Im Rahmen des Projekts wurden entsprechende Instrumente und Strategien für Unternehmen des Clusters Optik entwickelt. Unter anderem wurde der Arbeitskreis Fachkräfte ins Leben gerufen, um die Akteure besser zu vernetzen, Erfahrungen auszutauschen und die Kräfte für die Fachkräfteentwicklung zu bündeln. Als Highlight im Jahr 2016 präsentierte *AlFaClu* in der Karriere-Lounge der „micro photonics" ausgewählte Zwischenergebnisse, darunter Konzepte und Instrumente für Wissensmanagement und Personalentwicklung, und diskutierte sie mit Vertretern aus Industrie, öffentlicher Verwaltung und Politik.

Photonics
Photonik

Photonik

Im Forschungsbereich Photonik deckt das FBH ein breites Spektrum an Entwicklungen zu Diodenlasern und Leuchtdioden (LEDs) ab, die auf die jeweilige Anforderung zugeschnitten werden. Das Portfolio reicht von der Bearbeitung grundlagenorientierter Fragestellungen bis hin zur Entwicklung von einsatzfähigen Diodenlasermodulen und Prototypen. Es umfasst Galliumarsenid-basierte Diodenlaser, die vom infraroten bis zum ultravioletten Spektralbereich emittieren, sowie Laserdioden und LEDs auf Galliumnitrid-Basis, die im UV-Spektralbereich abstrahlen. Aktuell setzt das FBH die folgenden Schwerpunkte:

- ***Hochleistungs-Diodenlaser*** – Breitstreifenlaser, Laserbarren und Stacks, optimiert auf hohe Ausgangsleistungen. Sie werden u.a. als Pumplaser und für die direkte Materialbearbeitung genutzt.

- ***Lasermodule*** – in die miniaturisierten Module werden Optiken zur Strahlformung, externe Resonatoren, Elektronik und frequenzverdoppelnde Kristalle hochpräzise integriert. Auch die anschließende Kopplung in Glasfasern ist möglich. Sie eignen sich u.a. für den Einsatz in Displays oder der Medizintechnik.

- ***Lasersensorik*** – Diodenlaser, die speziell auf Anwendungen in der Sensorik und der Analytik zugeschnitten sind. Sie kommen u.a. in miniaturisierten, portablen Lasermesssystemen zum Einsatz, die Messungen von Raman-Spektren auch in stark fluoreszierenden Umgebungen ermöglichen.

- ***Lasermetrologie*** – in diesem Bereich werden ultra-schmalbandige Diodenlasermodule entwickelt. Dank der Hochpräzisionsmontage sind sie besonders kompakt und robust und eignen sich daher auch für Weltraumanwendungen.

- ***GaN-Optoelektronik*** – auf diesem Gebiet entwickelt das FBH Nitrid-Laserdioden und UV-Leuchtdioden, insbesondere für den UV-B- und UV-C-Spektralbereich. Die LEDs eigenen sich u.a. für die Oberflächenbehandlung und die Pflanzenbeleuchtung.

Das erforderliche grundlegende Know-how hält das Department Optoelektronik bereit.
Es entwirft, realisiert und charakterisiert die zugehörigen Diodenlaser-Chips.

Photonics

Within its photonics research area, FBH covers a broad range of diode laser and LED developments that are tailored precisely to fit individual requirements. The portfolio ranges from basic research to the development of ready-to-use modules and prototypes.
It comprises gallium arsenide based diode lasers, emitting from the infrared to the UV spectral range, as well as laser diodes and LEDs based on gallium nitride with emission in the UV spectral range. The FBH currently focuses on the following topics:

- ***High-power diode lasers*** – broad area lasers, laser bars, and stacks optimized for high output powers. They are used as pump lasers as well as for direct materials processing.

- ***Laser modules*** – optics for beam shaping, external resonators, electronics, and crystals for frequency doubling are integrated with diode lasers into miniaturized modules. Subsequent coupling into glass fibers is also possible. These light sources are ideally suited for applications including displays and medical technology.

- ***Laser sensors*** – diode lasers that are customized for applications in sensors and analytics. They are employed, e.g., in miniaturized, portable laser measurement systems that enable Raman spectra to be measured even in highly fluorescent environments.

- ***Laser metrology*** – ultra-narrowband diode laser modules are developed in this field. Due to high-precision mounting they are particularly compact as well as robust and thus perfectly suited for space applications.

- ***GaN optoelectronics*** – FBH develops nitride laser diodes and UV light-emitting diodes (LED) especially for the UV-B and UV-C spectral range. Suitable applications for LEDs include surface treatment and plant growth lighting.

The required basic know-how for these developments is provided by the Optoelectronics Department. It designs, realizes, and characterizes the corresponding diode laser chips.

Sampled gratings – E-beam-based grating technology for widely tunable laser diodes

Widely tunable diode lasers are key components for optical systems used in industrial and biomedical sensor applications. Nowadays, sampled grating (SG) distributed Bragg reflector (DBR) lasers based on InP are well established devices, offering wide wavelength tuning around 1.3 µm and 1.55 µm. This contrasts with the short wavelength GaAs material system, where the integration of gratings with reduced periods and very high coupling coefficient k – as required for µm long functional grating burst – is challenging. Recently, we have developed a GaAs-based SG-DBR laser with a center wavelength around 970 nm (Fig. 1). The device has a novel vertical structure which allows to implement gratings with very high k as well as to avoid oxygen incorporation at the regrowth interface and thus degradation of the device performance. We therefore applied GaAs layers surrounding the regrowth interface instead of AlGaAs waveguide layers with their high affinity to oxygen.

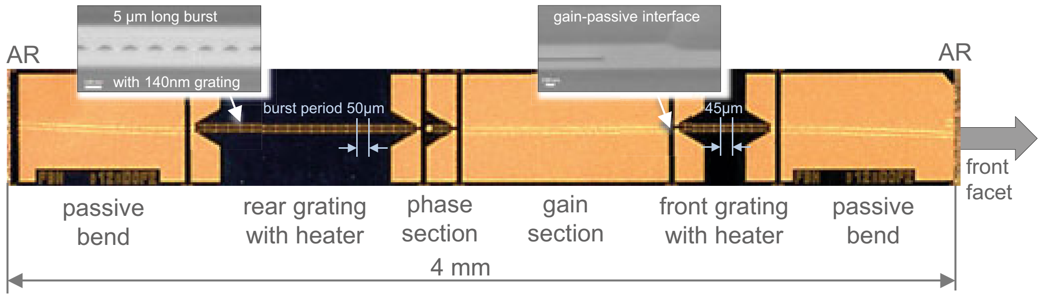


Fig. 1. Top down photography of the realized SG-DBR laser.

The vertical layer structure is grown in two steps by metal-organic vapor phase epitaxy (MOVPE) on 3-inch GaAs wafers. It contains an InGaAs single quantum well (SQW) asymmetrically embedded in GaAs confinement and AlGaAs cladding layers. The first epitaxy stops after the growth of the first part of the p-confinement layer above the SQW. The n-confinement layer beneath the SQW comprises two InGaP layers acting as etch stop and grating layers. Placing the grating layer near the intensity peak of the vertical mode ensures a high coupling coefficient k. Two lithographical steps – each followed by selective wet etching, resist removal, and surface cleaning – are performed before overgrowth. The sampled gratings are formed into the lower InGaP layer. Grating bursts with a length of 5 µm are defined with E-beam (Vistec SB251) in ma N2401 resist. The bursts are repeated with periods of 50 µm and 45 µm for the rear and front grating, respectively. Within a burst, the gratings have a period of 143 nm and a duty cycle of 50 %. Before the overgrowth, we apply $(NH_4)_2S$ cleaning and CBr_4 in-situ surface etching to suppress the oxygen concentration at the regrowth interface. After completing the second epitaxy, a standard ridge waveguide laser fabrication process follows.

An SG-DBR is anti-reflection (AR) coated and mounted p-side up on C-mount for subsequent measurements. The optical output power measured on the front facet is 30 mW when a current of 150 mA is applied to the gain section. The light is launched into a standard single mode fiber and connected to an optical spectrum analyzer to capture the optical spectra. Fig. 2 summarizes the measured wavelengths in dependence of the currents applied to the front and rear heater sections in a color scale. Stripes of similar colors indicate areas of the same Vernier mode. Five periodic areas with up to ten different wavelengths can be distinguished. The wavelength of a single Vernier mode rises if both heater currents are increased. Ten optical spectra are shown in Fig. 3 for a fixed front heater current of 250 mA. The Vernier modes have a side mode suppression of 40 dB, a spacing of 2.3 nm, and the spectral distance between the first and the tenth mode is 20.6 nm.

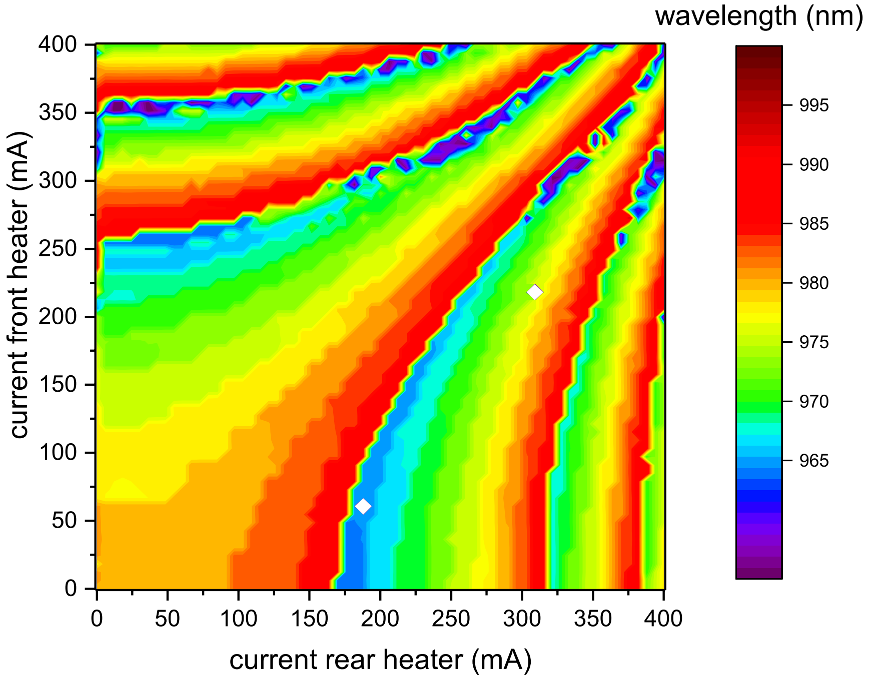


Fig. 2. Measured laser wavelengths in dependence of the currents applied to the rear and front heater (current gain section 150 mA, C-mount temperature 20 °C).

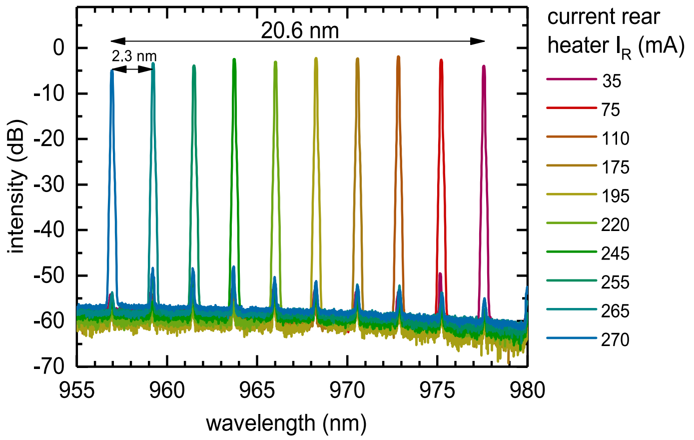


Fig. 3. Spectra of the realized SG-DBR laser for different rear heater currents (current gain section 150 mA, C-mount temperature 20 °C).

Due to this thermal wavelength control, the developed SG-DBR laser is interesting for a number of industrial and biomedical sensor applications that require a wavelength tuning speed in the microsecond range.

Parts of this work have been carried out under the *Mid TECH* project funded by the European Union's Horizon 2020 program under grant agreement No. 642661.

Weit abstimmbare Diodenlaser sind zentrale Komponenten für optische Sensorsysteme in industriellen und biomedizinischen Anwendungen. In diesem Zusammenhang haben sich InP-Laser mit hoher Durchstimmbarkeit um 1,3 µm und 1,55 µm etabliert, die auf Tastgittern basieren. Bei kurzwellig emittierenden GaAs-Laserdioden konnte eine solche weite Abstimmbarkeit der Wellenlängen bislang nicht demonstriert werden. Ursache hierfür ist die Schwierigkeit, Gitter mit sehr großen Koppelkoeffizienten zu integrieren, wie sie für wirksame Gitterpakete in Tastgittern erforderlich sind. Am FBH wurde nun ein GaAs-Laser mit Tastgittern realisiert, der um 970 nm emittiert und eine kontrollierte Wellenabstimmbarkeit von > 20 nm demonstriert. Der Chip basiert auf einer neu entwickelten Laservertikalstruktur, die in zwei Epitaxieschritten erzeugt wird. Zwischen diesen Schritten werden 5 µm lange Gitterpakete hergestellt, die jeweils aus Gittern mit einer Periode von 143 nm bestehen, die mittels E-Beam-Lithografie strukturiert werden.

Publications

O. Brox, M. Tawfieq, P. Della Casa, P. Ressel, B. Sumpf, G. Erbert, A. Knigge, M. Weyers, H. Wenzel, "Realisation of a widely tunable sampled grating DBR laser emitting around 970 nm", IET Electronics Letters , DOI: 10.1049/el.2017.0521 (2017).

P. Della Casa, O. Brox, A. Knigge, B. Sumpf, M. Tawfieq, H. Wenzel, M. Weyers, G. Tränkle, "Integration of active, passive and buried-grating sections for a GaAs-based, widely tunable laser with sampled grating Bragg reflectors", Conf. Proceed. Compound Semiconductor Week, Berlin, DE (2017).

M. Tawfieq, H. Wenzel, O. Brox, P. Della Casa, B. Sumpf, G. Tränkle, "Concept and numerical simulations of widely tunable GaAs-based sampled-grating diode laser emitting at 976 nm", IET Optoelectronics, DOI: 10.1049/iet-opt.2016.0068 (2017).

Optically pumped GaN DFB lasers with 10th-order laterally coupled surface gratings

Laser diodes with a stable emission wavelength in the blue-violet spectral region and a narrow linewidth are promising light sources for spectroscopy, atomic clocks, medical applications, laser displays as well as for undersea optical communication. Typically, the narrow linewidth of a laser diode is achieved by a Bragg grating implemented into the device. Although optically or electrically pumped GaN-based lasers with low-order (1st, 2nd or 3rd) Bragg gratings have already been reported, their realization is technically challenging. This is due to the short emission wavelength, resulting in small grating dimensions for these lasers. A period of about 80 nm, for example, is required for a 1st-order Bragg grating. Furthermore, to achieve a reasonable overlap between grating and optical mode, previously reported DFB lasers call for a grating in close distance to the active region. This can be accomplished by using high-precision e-beam lithography, preferably in conjunction with a two-step epitaxial growth process of high cleanliness. In order to realize DFB laser diodes in a simpler way we have investigated a new approach based on high-order surface gratings. Their processing technology is much more straightforward compared to epitaxial overgrown gratings of low order.

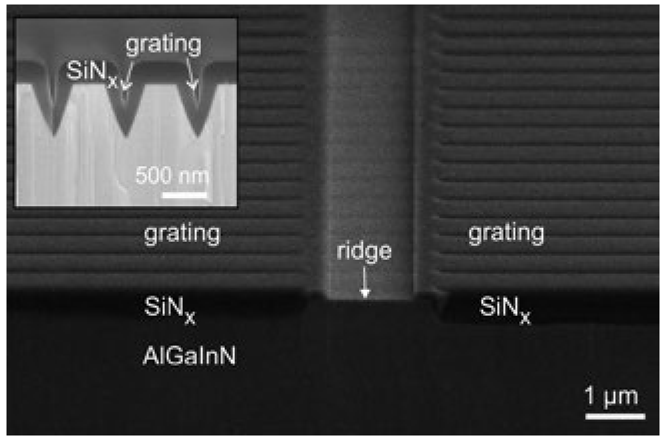


Fig. 1. Bird's eye-view SEM image of the LC-DFB structure; inset: cross section SEM image of the V-shaped grooves.

At FBH, we have started the comprehensive development of laterally coupled distributed-feedback (LC-DFB) lasers based on GaN using 10th-order surface Bragg gratings. According to simulation results a 10th-order grating with an etch depth of 600 nm (i.e. around 10 nm below the bottom quantum well) and a groove width of < 80 nm is favored to achieve a high reflectivity > 0.9. The fabrication of such gratings by conventional i-line photolithography (resolution of 300 nm) is possible by employing surface gratings with V-shaped grooves. Such grooves can be realized by exploiting redeposition effects from sputtering during inductively coupled plasma etching using heavy ions like BCl$_3$, as shown in Fig. 1. The narrow tips of the grooves correspond to a high duty cycle of the grating at the point where the mode intensity is large. After fabrication of the grating the wafers were covered with 250 nm thick plasma-enhanced chemical vapor deposited SiN$_x$, and a 1.5 μm wide opening (W$_o$) was structured on the ridges to define the aperture for later optical pumping. The laser bars were optically pumped with a pulsed ArF laser operated at a pulse repetition rate of 50 Hz and 5 ns pulse width with an emission wavelength of 193 nm. As shown in Fig. 2(a), single peak emission with a resolution-limited half width of 0.06 nm was achieved for the LC-DFB laser at a wavelength of 404.2 nm. Furthermore, the measured temperature sensitivity of the LC-DFB lasing wavelength is a factor of three smaller than that of the ridge waveguide Fabry-Perot (RW-FP) laser, as shown in Fig. 2(b). The spectral shift of the RW-FP and the LC-DFB lasers is 0.057 and 0.019 nm/K in the temperature range from 30 °C to 70 °C, respectively. For the LC-DFB laser the shift of the emission wavelength with temperature is predominantly governed by the temperature dependence of the effective refractive index of the optical mode and much less by the modal gain spectrum, which is the dominant factor for the RW-FP laser operating around the gain peak. The data clearly confirms that the high-order laterally coupled grating acts as wavelength-selective element, i.e., the optical mode effectively couples to the grating.

After successfully realizing these optically pumped lasers with laterally coupled high-order surface gratings we plan to extend this approach to current-injection LC-DFB laser diodes. This concept offers the advantage of a greatly simplified fabrication technology for electrically pumped LC-DFB lasers with the current injection region separated from the grating region by (a) using n-type GaN substrates instead of sapphire, (b) including p-type doping in the GaN and AlGaN layers above the quantum wells, and (c) depositing p-contact and n-contact metals on the wafers after the fabrication of the surface grating.

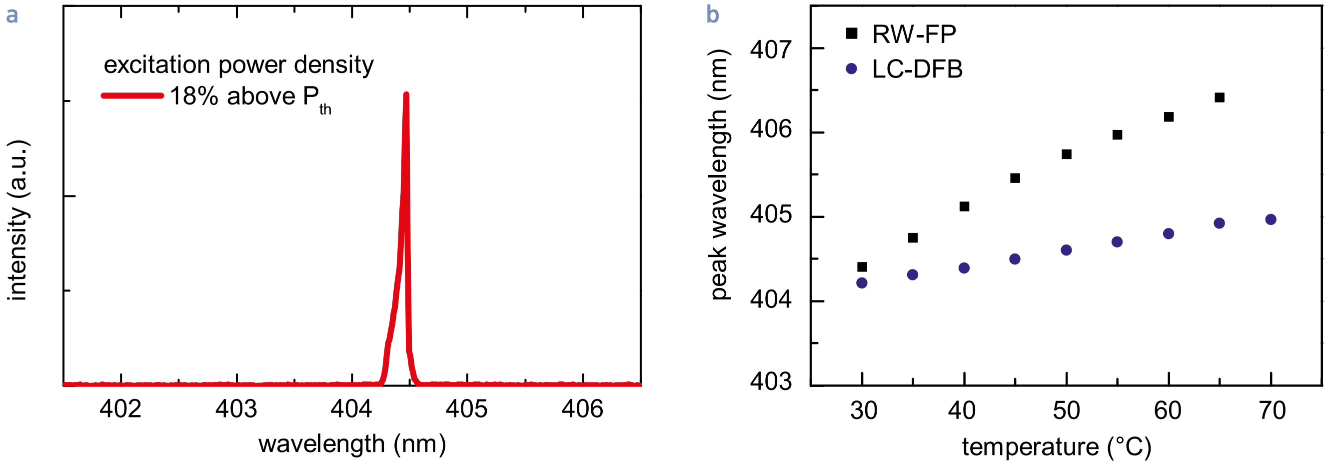


Fig. 2. (a) High-resolution emission spectra of the LC-DFB laser (at 18 % above threshold) and (b) temperature dependence of the emission peak wavelength of a RW-FP and a LC-DFB laser.

This work was supported in part by the European Fund for Regional Development of the European Union in the framework of the Berlin-Polish joint project *brilliant high power violet emitting laser diodes (BriVi)*, administrated by the Investitionsbank Berlin within the ProFIT program under Contract 10157699 and in part by the German Research Foundation in the Collaborative Research Centre 787.

Einsatzgebiete von Laserlichtquellen wie etwa die Spektroskopie benötigen Laserstrahlung hoher Brillanz. Deshalb werden häufig monolithische Bragg-Gitter niedriger Ordnung in Laserdioden implementiert. Im Fall von kurzwellig emittierenden Laserdioden auf der Basis von GaN sind diese jedoch technologisch sehr aufwändig herzustellen, da insbesondere Lithografieprozesse hoher Auflösung notwendig sind. Am FBH wurden nun erstmalig mithilfe von Standardlithografieprozessen DFB-Laser mit lateral an einen Rippenwellenleiter gekoppelten Oberflächengittern 10. Ordnung realisiert. Diese zeigen – im Gegensatz zu Lasern ohne Gitter – bei optischem Pumpen eine Einzelpeakemission bei 404 nm mit einer spektralen Breite von 0,06 nm. Die geringe Peakverschiebung mit der Temperatur von 0,019 nm/K bestätigt die effektive Kopplung des Gitters an die Lasermode. Aufbauend auf diesen Ergebnissen ist eine GaN-basierte DFB-Laserdiode mit einfacher Herstellungstechnologie greifbar nahe.

Publication

J.H. Kang, M. Martens, H. Wenzel, V. Hoffmann, W. John, S. Einfeldt, T. Wernicke, M. Kneissl, "Optically pumped DFB lasers based on GaN using 10th-order laterally coupled surface gratings", IEEE Photon. Technol. Lett., vol. 29, no. 1, pp.138-141 (2017).

Tapered diode lasers with 10 W diffraction-limited output power

Developing diode lasers with sufficient optical output power, diffraction-limited beam quality, and narrowband laser emission is still a challenge. Such lasers are required for many demanding applications, for example, nonlinear frequency conversion. Here, a nonlinear crystal is used to convert the laser emission wavelength to a spectral range currently not addressed by available direct emitting devices. Suitable lasers ideally provide several watts of diffraction-limited output power and spectral emission bandwidths below the acceptance bandwidths of the applied non-linear crystals, typically < 100 pm.

These requirements are accomplished by wavelength-stabilized tapered diode lasers. Such diode lasers consist of a ridge waveguide and a tapered amplifier. The waveguide design ensures diffraction-limited laser emission, intrinsically coupled into the amplifier in order to intensify the optical output power. Internal wavelength stabilization is obtained either by distributed feedback along the device or a passive distributed Bragg reflector (DBR) as rear side cavity mirror. In the latter case, anti-reflection coated rear facets provide an additional spatial mode filtering. One major challenge in the tapered laser development is the suppression of unwanted modes propagating through the device. At FBH, DBR tapered diode lasers with 8 W of diffraction-limited output power have already been presented at emission wavelengths in the range of 980 nm - 1120 nm.

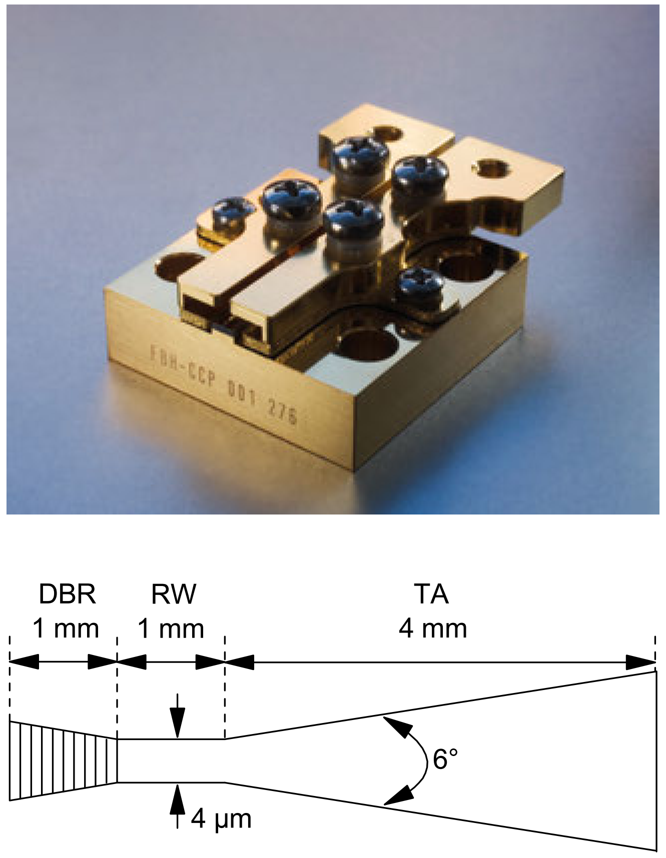


Fig. 1. DBR tapered diode laser on conduction cooled package mount (top). Schematic drawing of the lateral laser layout for the newly developed tapered diode lasers (bottom).

For the recent development, DBR tapered diode lasers with an improved DBR design and ion implantation applied along the mesa structure have been manufactured. The laser structure is based on an InGaAs triple quantum well embedded in an asymmetric super large optical cavity. At a total length of 6 mm, the laser layout consists of a tapered 7th order DBR grating, a 4 µm ridge waveguide, and a 6° tapered amplifier (Fig. 1). The 1 mm grating is manufactured using electron beam lithography. Its tapered design in conjunction with the selected vertical structure allows for a diffraction efficiency twice as high compared to the previous straight layout. Separate contacts for waveguide and amplifier enable independent control over these two sections.

The laser facets are passivated and anti-reflection coated ($R_{Rear} < 0.03$ %, $R_{Front} = 0.1$ %). For laser characterization, the devices are mounted p-side up on copper tungsten heat spreaders on 25 mm x 25 mm conduction cooled package mounts. At a heat sink temperature of 15°C and a waveguide injection current of 200 mA such a device provides an optical output power of 13.6 W (Fig. 2). The maximum electro-optical efficiency neglecting the electric power applied to the waveguide is 50 % with 44 % still obtained at the highest applied injection current. Due to the intrinsic wavelength stabilization narrowband emission is obtained over the whole power range. At maximum output power the peak emission wavelength and the spectral width at full width at half maximum are 1027.70 nm and 22 pm, respectively (inset Fig. 2).

The spatial characteristics are measured according to ISO Standard 11146. The obtained beam waist intensity distribution at the highest injection current shows a defined 7.6 µm wide central lobe ($1/e^2$) and a certain number of side lobes (Fig. 3). Integration reveals that 76 % of output power is contained in the central lobe, corresponding to a diffraction-limited output power of 10.3 W. With a lateral far field angle of 11.6° ($1/e^2$) the obtained beam propagation ratio is $M^2 = 1.1$.

A comparison to the previous layout with straight DBR gratings revealed significantly different dependencies of the diffraction-limited output power on the injection current applied to the ridge waveguide. For the straight design, an injection current span of 400 mA changes the central lobe power by about 20 %, in favor of low currents. Applying the same injection currents to lasers with the new design reduces the change in central lobe power to about 5 %. At all operating points, the highest central lobe power is obtained with the new lasers layout.

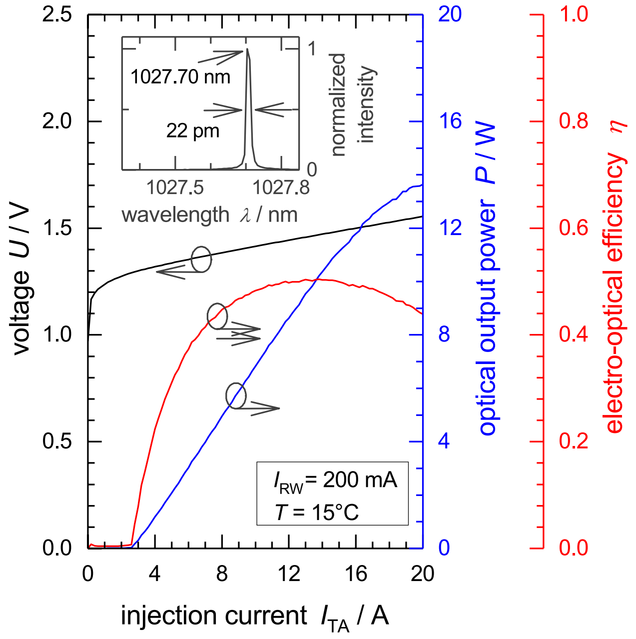


Fig. 2. Power-voltage-current characteristics for the newly developed 1030 nm DBR tapered diode laser. Inset: Corresponding single emission spectrum at 13.6 W of the optical output power.

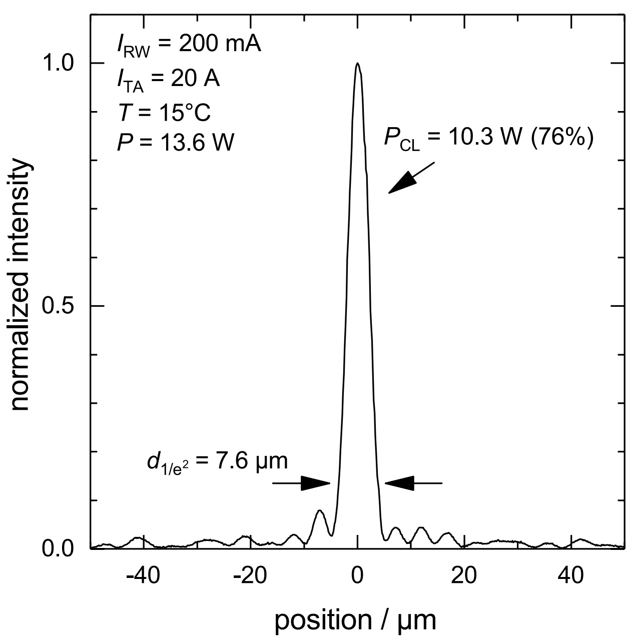


Fig. 3. Beam waist intensity distribution at 13.6 W of the optical output power.

Considering all results, the significant improvement in laser performance increases the application potential for tapered diode lasers for many demanding applications including nonlinear frequency conversion.

This work was supported by the EU Seventh Framework Program, Information and Communication Technologies, contract no. 317744.

Trapezlaser bieten den Vorteil hoher optischer Ausgangsleistung bei gleichzeitig sehr guter Strahlqualität. Zudem sorgen interne wellenlängenselektive Gitter für eine spektral schmalbandige Laseremission. Somit ist diese Art von Diodenlasern auch für anspruchsvolle Anwendungen wie etwa die nicht-lineare Frequenzkonversion geeignet. Bisher erreichten am FBH entwickelte DBR-Trapezlaser 8 W beugungsbegrenzte Leistung im spektralen Bereich von 980 nm - 1120 nm. Neu entwickelte 1030 nm Trapezlaser stellen durch eine zusätzliche Implantation entlang des Rippenwellenleiters sowie einer Optimierung der internen Gitter nun sogar bis zu 10,3 W beugungsbegrenzte Leistung bereit. Dies entspricht 76 % der emittierten Lichtleistung. Mit der internen Wellenlängenstabilisierung liegt die spektrale Breite der Laseremission bei etwa 22 pm über den gesamten Leistungsbereich. Diese verbesserten Eigenschaften erhöhen das Anwendungspotenzial von Trapezlasern insgesamt und eröffnen sogar neue Anwendungsfelder.

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High-power high-efficiency single-mode 9xx nm RW laser with low divergence

High-power single spatial mode diode lasers emitting in the 9xx nm region are interesting for a lot of applications: pumping fiber amplifiers in telecommunications, as light sources in sensing systems, and as key elements of high-power laser machines in materials processing using dense wavelength multiplexing. Narrow-stripe ridge waveguide (RW) lasers offer the advantage of a low and stable astigmatism value, compared to other sophisticated semiconductor laser designs. As a result, they ensure an easy use of outgoing laser light. On the other hand, power conversion efficiency (PCE) is a big challenge for narrow-stripe lasers in high-power applications due to their relatively high series resistance and power density. At FBH, RW laser designs using optimized semiconductor layer structures have been developed to pave the way beyond the 1 W level in the 9xx nm wavelength range whilst keeping PCE near 60 % and beam quality below $M^2 < 1.5$.

The main design issue for a narrow-stripe laser is the balance of mode size, which should be large enough to avoid nonlinearities and self-destroying by excessive power density. On the other hand, it should be small enough to avoid higher order modes to keep an excellent beam quality.

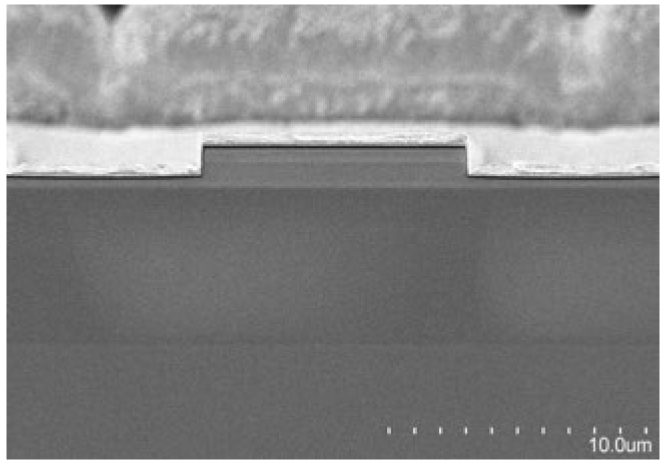

Fig. 1. MESA structure of mounted RW laser (SEM picture).

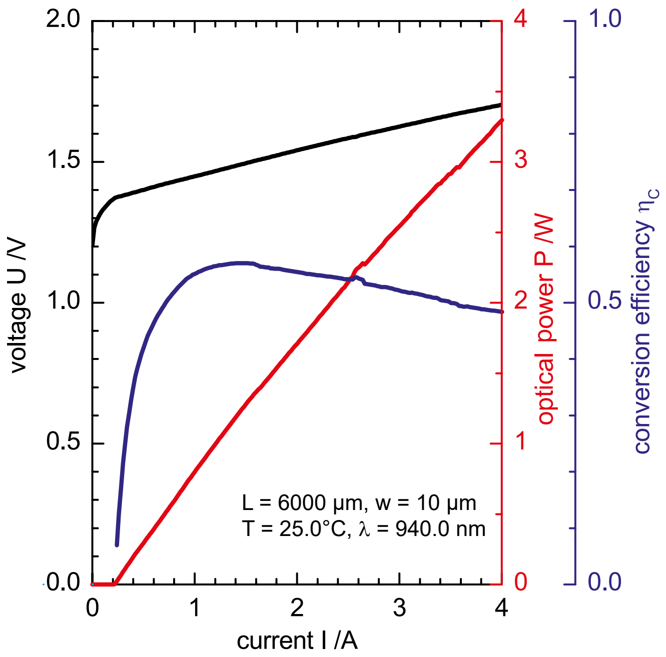

Fig. 2. Power/current characteristics of an RW laser with new design.

We used an edasloc (extremely double asymmetric large optical cavity) structure as vertical waveguide. This structure has a thin p-doped waveguide of only about 200 nm and a large, about 5 µm thick n-doped waveguide. Accordingly, the laser mode is concentrated in the low loss n-region of the waveguide mainly. The waveguide thickness and material composition was chosen to obtain a large size of the fundamental mode and a low number of higher order modes. Lasing of these higher order modes is suppressed by higher optical losses using specifically designed refractive index and doping profiles.

Due to the thin p-waveguide, the residual layer thickness beyond the mesa above the quantum well is quite small in the RW laser design. Therefore, this structure has low lateral current spreading, which enables high output of the fundamental mode in the watt range using large mesa widths up to 15 µm. So, lower series resistance and lower optical intensity is the key for higher power and PCE, compared to common RW lasers which have 3 µm mesa widths, typically.

The layer structure was grown with MOVPE; the processing steps were done using 3" full wafer technology. FBH's specific dry etching technology was used to realize definite mesa widths and depths with high precision, as shown in the SEM picture Fig. 1. The other processing steps utilized, were typical standards for compound semiconductor GaAs-based laser technology. Optical highly stable AR coatings were applied using FBH's unique facet technology. Such laser facets must be able to resist power densities of about 20 MW/cm², which are expected at output power levels in the desired range of 2 W and more. For characterization purposes, the devices were mounted p-side down on CuW submounts.

In Fig. 2 the power current characteristics of an RW laser with a mesa width of 10 µm are shown. This laser achieved an output power of more than 3 W without exhibiting thermal roll over. The PCE at 1 W is nearly 60 % and about 50 % at 3 W. In Fig. 3 the lateral far field is shown, demonstrating an excellent beam quality up to an output power of 1 W. The RW laser also degrades only to M^2 values of 2 at a higher output up to 3 W. In addition, the beam quality at high output powers could be improved by including lateral mode filters. In Fig. 4 the far field pattern of such a laser is shown at a power of 2.5 W. The beam quality is nearly 1. The low values for divergence of 8.4° in lateral and 30° in vertical direction at 95 % power level demonstrate the benefits of the enlarged mode size.

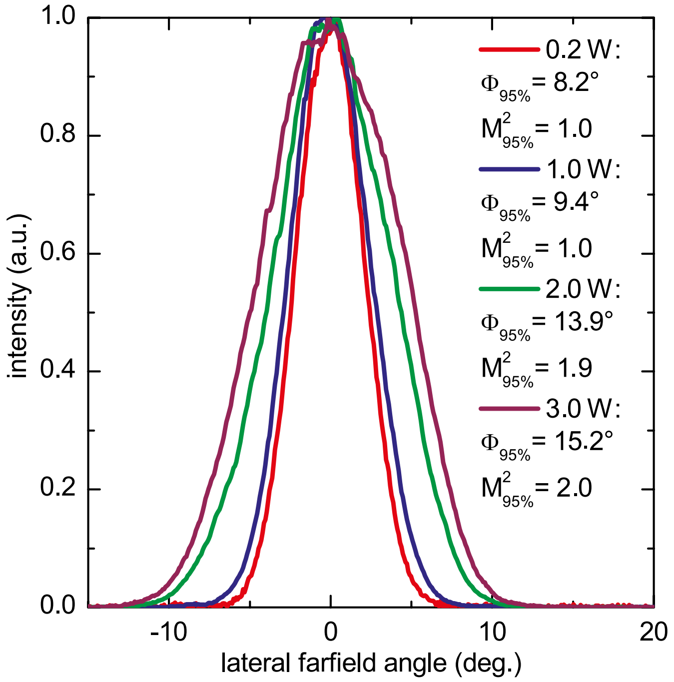

Fig. 3. Lateral farfield pattern at different power outputs.

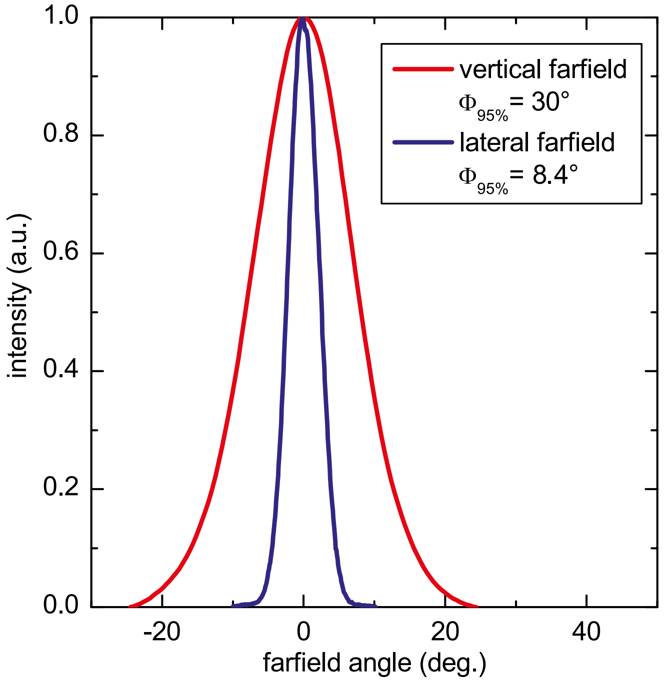

Fig. 4. Beam pattern of newly designed RW laser at 2.5 W output power.

These excellent beam characteristics will allow an easy use in fiber coupling and in external cavities to improve the spectral properties for a great variety of applications. Current research at FBH is now focusing on further optimizing the laser design for specific applications.

Das FBH hat Rippenwellenleiter (RW)-Diodenlaser mit schmaler Streifenbreite entwickelt, die eine edasloc-Struktur (extreme, double-asymmetrical super-large optical cavity) als vertikale Wellenleiterstruktur nutzen. Diese neuen Designs ermöglichen eine vergleichsweise hohe laterale Modengröße und liefern monomodige Ausgangsleistungen im Bereich von 2 Watt und höher. Verglichen mit derzeit marktüblichen RW-Standardlasern sind die bei 95 % der Ausgangsleistung gemessenen Divergenzwinkel von 10° und 30° in lateraler und vertikaler Richtung zudem sehr niedrig. Mit ihrem Wirkungsgrad um 55 % und dem sehr niedrigen Astigmatismus eignen sich diese Diodenlaser ideal für Anwendungen wie etwa in der optischen Kommunikation und Sensorik oder als zentrale Bauelemente in Hochleistungs-Lasersystemen. Sie ebnen 9xx nm Diodenlasern den Weg in Richtung hoher Ausgangsleistungen >1 Watt bei zugleich hohem Wirkungsgrad um 60 % mit einer Strahlqualität unter $M^2 < 1{,}5$. Die aktuellen Forschungsarbeiten am FBH konzentrieren sich nun darauf, dieses Laserdesign zielgerichtet für spezifische Anwendungen zu entwickeln.

Publications

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Advanced kilowatt-class diode laser bars

The FBH High-Power Diode Laser Lab develops diode lasers with the highest possible optical output power P_{opt} and power conversion efficiency η_E for minimal operation cost in €/W, delivered with highest beam quality and reliability. Diode laser bars with 1 cm aperture are deployed in high volumes in industrial and scientific applications either directly or as pump sources for high-energy-class and high-power solid-state lasers, and continuously improved performance is required. Recent research at the FBH into 1 cm diode laser bars have increased both P_{opt} and η_E at high P_{opt}, for use in a range of pump applications. These studies were performed in close collaboration with the FBH's industrial partners to enable progress in laser applications and an efficient transfer into the market.

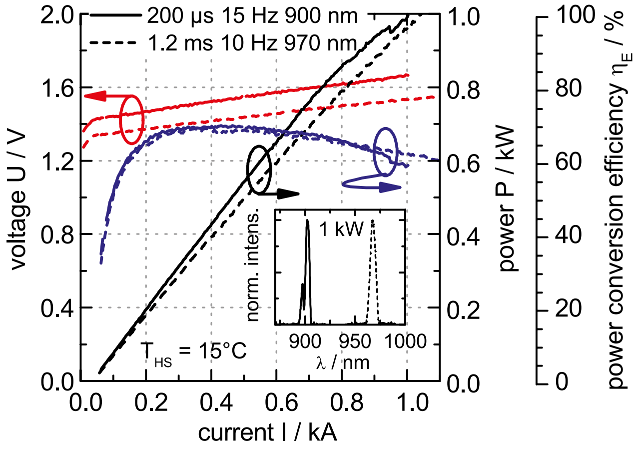

Fig. 1. Voltage, power, and efficiency vs. current for 1 cm bars for pumping Nd:YAG (900 nm) and Yb:YAG crystals (975 nm). Inset: spatially integrated intensity as a function of wavelength at 1 kW.

First, diode laser bars were developed for pumping of solid-state amplifier crystals in high-energy-class laser applications. Here, P_{opt} = 1 kW with high η_E was targeted for use in pumping established solid-state amplifier materials, namely Nd:YAG or Yb:YAG crystals, that need pulsed pump sources with wavelengths λ and pulse lengths τ of λ ~ 880 nm at τ ~ 200 µs and λ = 940 nm or 975 nm at τ ~ 1 ms, respectively. Enhanced epitaxial design, process technology, and bar packaging enabled prototype laser bars to operate for the first time with η_E = 70 % at P_{opt} = 400 W and η_E > 60 % up to P_{opt} = 1 kW [3, 4]. The use of long (4…6 mm) resonators and facet passivation played an important role in delivering high η_E at high P_{opt} and enabling failure-free high-power operation. Comparable performance was observed for bars operating at P_{opt} = 1 kW in the range λ ~ 890…970 nm, as shown in Fig. 1 for single bars mounted on kilowatt-class conductively cooled packages (CCPs, see Fig. 2). These studies were performed in collaboration with Jenoptik Diode Lab, as part of the Cryolaser project.

Second, diode laser bars were developed that were tailored for pumping alternative solid-state laser materials for next-generation high-energy-class pulsed laser systems, specifically Yb:CaF$_2$, which has a long upper-state lifetime so can be pumped using long excitation pulses (τ = 2 ms compared to τ = 1 ms in conventional Yb:YAG amplifiers). Long-pulse pumping allows more energy to be stored in the amplifier per pump laser, for reduced system cost. Here, P_{opt} = 600 W was targeted in τ = 2 ms pulses, for an energy of E_p > 1.2 J per pulse. Bars were developed that operate at λ = 940 nm and 975 nm, for pumping the broad main absorption peak and for the narrow zero-phonon-line respectively. Bars at λ = 940 nm used epitaxial layer designs tailored for high η_E and bars at λ = 975 nm utilized epitaxial designs tailored for reasonable η_E and extremely low vertical divergence (13° full width half maximum, 25° at 95 % power content) for low-loss external wavelength stabilization. Initial results are shown in Fig. 3 for single bars mounted on CCPs, with η_E > 60 % (λ = 940 nm) and η_E > 50 % (λ = 975 nm) at P_{opt} = 600 W (external wavelength stabilization will follow). Bars mounted in eight-bar passively cooled stacked arrays showed comparable performance [1]. These studies were performed in collaboration with Lastronics and DILAS as part of the Doppelpump project.

Fig. 2. Kilowatt-class bar mounted on low-resistance conductively-cooled heatsink.

Third, diode laser bars were developed for power scaling, performance improvement and cost reduction for a new generation of continuous wave (CW) Yb:YAG high power disc lasers for material processing applications. Bars with maximum η_E at P_{opt} = 1 kW in CW mode were sought, emitting at λ = 940 nm. High-performance, innovative diode laser bars and bar coolers were developed in close cooperation between the FBH and Trumpf's new advanced technology research group in Berlin, and these have enabled a step improvement in bar performance. CW test results on initial prototypes are shown in Fig. 4, where η_E > 65 % is observed at P_{opt} = 650 W without failure. Subsequent development has enabled scaling to CW powers P_{opt} > 1000 W per bar [2].

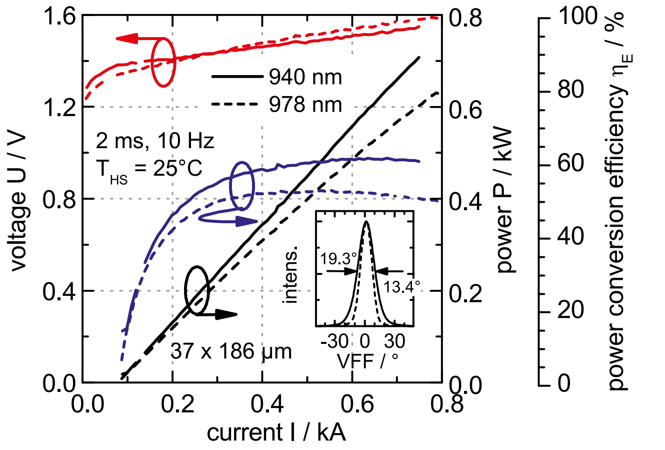

Fig. 3. Voltage, power, and efficiency vs. current for 1 cm bars for pumping Yb:CaF$_2$ crystals (940 nm direct, 975 nm for VBG stabilization). Inset: optical intensity vs. vertical angle (FWHM noted).

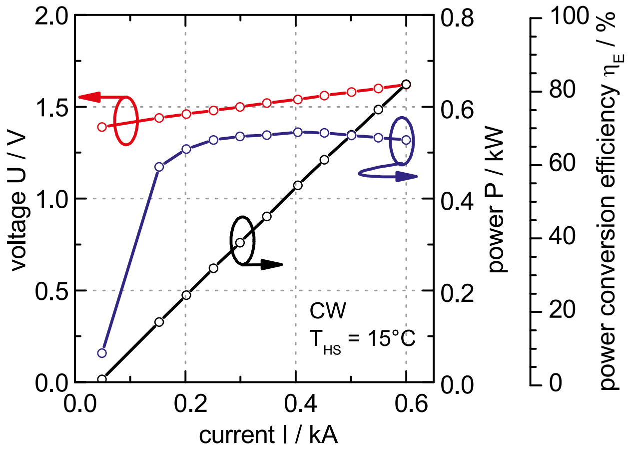

Fig. 4. Voltage, power, and efficiency vs. continuous wave current for 1 cm bars for pumping Yb:YAG disk lasers.

In summary, ongoing FBH design and technology developments have enabled kW-class bars to be made available that are tailored for peak performance in multiple different applications in the pumping of solid-state lasers. Close collaboration with industrial partners helps ensure the efficient transfer to market.

Parts of these activities were funded by the Leibniz-Association under Grant SAW-2012-FBH-2 and by the German Federal Ministry for Economic Affairs and Energy (BMWi) under Grant KF2194510DF4.

Das FBH entwickelt in Kooperation mit industriellen Partnern Hochleistungslaserbarren mit 1 cm Apertur mit maßgeschneidertem Design für den effizienten Betrieb bei hohen optischen Leistungen. Dadurch lassen sich laufende Kosten in €/W minimieren und gleichzeitig Strahlqualität sowie Lebensdauer maximieren. So hat das FBH zusammen mit Jenoptik Laserbarren entwickelt, welche erstmals eine Effizienz von η_E = 70 % bei einer Leistung von P_{opt} = 400 W und η_E > 60 % bei P_{opt} = 1 kW erreichen. Sie zielen auf den Einsatz als Pumpquellen in Hochenergie-Lasersystemen mit aktiven Materialien, wie z.B. Nd:YAG bzw. Yb:YAG. Alternative aktive Materialien von Festkörperlasern, wie etwa Yb:CaF$_2$, benötigen lange Anregungspulse. In Kooperation mit Lastronics und DILAS hat das FBH Laserbarren für den quasi-Dauerstrichbetrieb (2 ms, 10 Hz) entworfen, die Spitzenleistungen von 600 W mit einer Pulsenergie von 1,2 J erzielten. In Kooperation mit TRUMPF entstanden Laserbarren, welche erstmals 1 kW optische Leistung im Dauerstrichbetrieb mit einer Effizienz von über 55 % bei einer Wellenlänge von 940 nm im Dauerstrichbetrieb aus einem einzelnen Laserbarren bei Raumtemperatur emittierten. Die anhaltende und enge Kooperation des FBH mit industriellen Partnern ermöglicht es, mit neuen Ideen, Innovationen und Technologien effizient auf dem Markt zu agieren.

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1030 nm ps pulse laser source with nanojoule energies – adjustable by mode locking or pulse gating operation

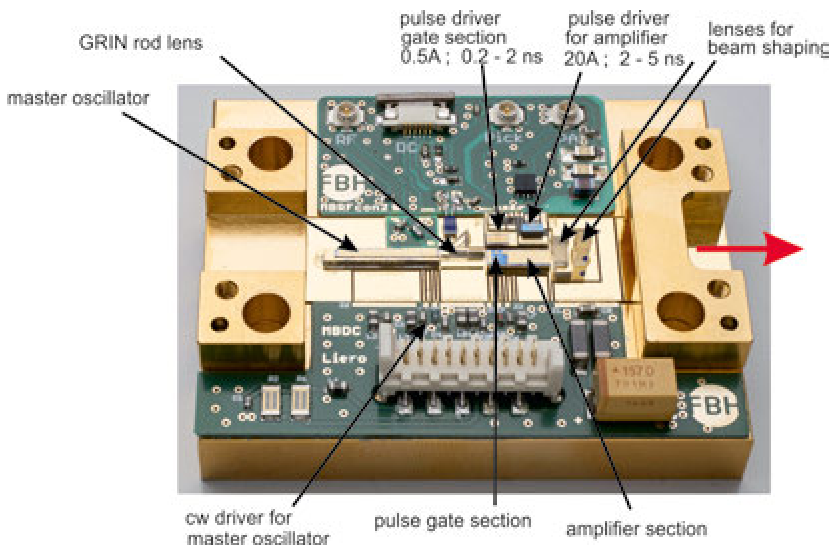

Fig. 1. Developed picosecond light source on a 5 x 4 cm micro bench.

Flexible light sources delivering optical picosecond pulses with repetition frequencies ranging between kHz and MHz and achieving peak powers from several tens of watts are highly requested. They are attractive, for example, as seed lasers for solid-state and fiber lasers, especially for fiber laser pulses when a stable amplitude (no first relaxation peak) and wavelength are needed. This can be achieved by pulse gating (cut-off pulses from a CW signal) in the time range > 250 ps. Further applications include LIDAR (automotive safety and 3D imaging), medical and biotechnology applications, free-space optical communication, spectroscopy as well as nonlinear frequency conversion.

Pulses shorter than 20 ps down to 1 ps or even less are needed, e.g., for systems in micromachining, precision measurements, THz imaging, and THz-time domain spectroscopy. So far, such short pulses cannot be generated by direct modulation of the laser diode itself (gain switching, Q-switching, or pulse gating) since this would require switching of current amplitudes in the ampere range within time intervals below 20 ps. However, mode locking is a well-known technique to generate short pulses with repetition rates in the GHz or high MHz range.

We have developed a world innovation compact 1030 nm picosecond light source that can be flexibly switched between pulse gating and passive mode locking operation. The laser module generates short optical pulses with a stable wavelength or picosecond pulses in the time range from 4 to 15 ps. It consists of a multi-section distributed Bragg reflector (DBR) laser as master oscillator (MO), an ultrafast multi-section optical gate, and a tapered power amplifier (PA). These components are mounted together with high frequency electronics and optical elements on a 5 x 4 cm micro bench shown in Fig. 1.

The MO is a 10 mm long ridge waveguide (RW) laser consisting of a 200 µm long saturable absorber, a 1500 µm long gain, an 8000 µm long cavity, a 200 µm long DBR, and a 100 µm long monitor section. It can be operated in two ways: CW for pulse gating and mode locking. In CW operation all sections, except DBR and monitor sections, are forward biased and driven by a constant current, whereas in mode locking regime the absorber section is reversed biased. In mode locking operation optical pulses with widths between 4 to 15 ps at a repetition frequency of ~ 4.2 GHz can be generated, which must be reduced for many applications. For this, a multi-section 2 mm ridge waveguide (RW) section is developed, monolithically integrated with a gain-guided tapered power amplifier (TPA) having a total length of 6 mm.

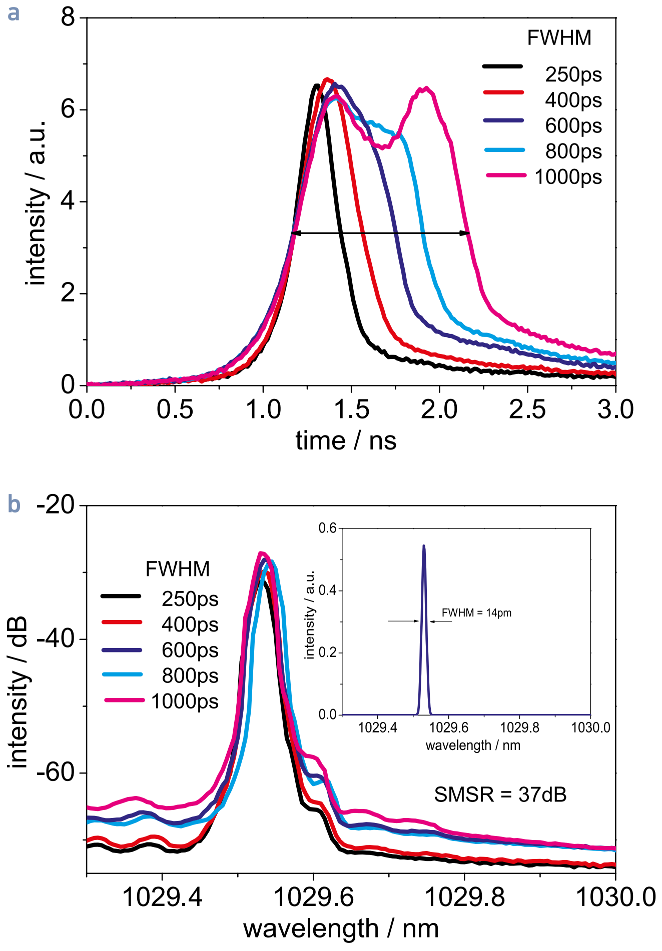

Fig. 2. Optical picosecond pulses (a) and spectral behaviors (b) under pulse gating operation. Inset: Spectrum on a linear scale with a FWHM of 14 pm, the resolution of the optical spectrum analyzer. A linewidth in the MHz range is assumed, which is typical for DBR lasers.

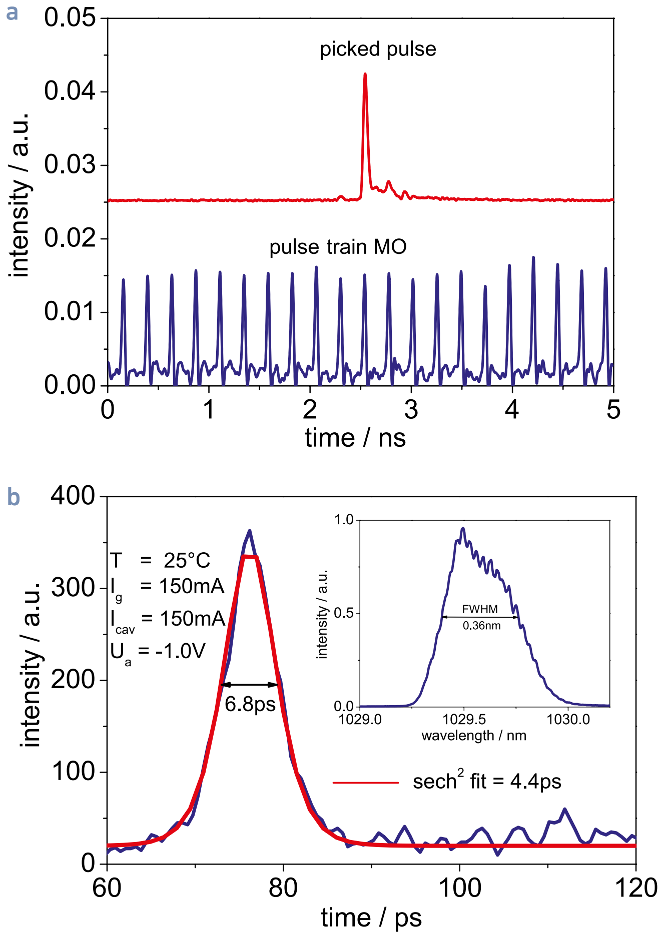

Fig. 3. Time (a) and spectral (b) behaviors under mode locking operation. Inset: Peak wavelength of 1029.65 nm and a spectral width (FWHM) of about 380 pm.

The 2 mm long RW section consists of an input zone to control the input intensity, a fast optical gate (OG), and a final section to minimize the feedback from the amplifier. The OG can be switched transparently or absorbingly by applying a short current pulse generated by an ultrafast high-frequency high electron mobility GaN transistor. The high-frequency electronics developed for the OG can be used for pulse gating (CW input) as well as for pulse picking (input of a pulse train from the MO) in the time range 0.2 to 2 ns.

Fig. 2 shows generated optical picosecond pulses (a) and spectral behaviors (b) under pulse gating operation at the output of the micro bench. A minimum pulse duration of 250 ps has been achieved. The pulse width can be continuously tuned by adjusting the duration of current pulse through the fast optical gate between 250 ps to 1 ns. Pulse powers of about 20 W have been reached for all pulse widths. Advantages of this operation mode are that no first relaxation peak occurs and the amplitude is stable. Optical spectra for the generated pulses are shown in Fig. 2(b). The emission peak wavelength of about 1029.5 nm and the spectral width are independent of the pulse width. The measured side-mode suppression rate is about 37 dB.

Results of mode locking operation are presented in Fig. 3. The generated pulse train of the MO (repetition frequency of 4.2 GHz) within 5 ns time duration, which is coupled into the optical gate, is shown in Fig. 3(a), blue curve. By injecting a current pulse into the OG section, a single optical pulse is picked and amplified in the tapered section, see Fig. 3(a), red curve. The measurement shows a reduction of the repetition frequency to 1 MHz. The tapered section can amplify the pulses to powers > 50 W depending on the repetition frequency. The repetition rate can be varied between 1 kHz and 20 MHz. Also, the pulse-to-pulse distance can be controlled by an external trigger source. Temporal measurements of the output of the compact ps source in mode locking operation were carried out using an autocorrelator. Fig. 3(b) shows an autocorrelation time trace of a picked pulse with a FWHM of 6.8 ps. By assuming a sech^2 pulse form (red curve), a pulse width of τ_{sech2} = 4.4 ps is calculated. The duration of the pulse from 4 ps to 15 ps can be changed with the applied reverse voltage to the absorber section.

These activities have been supported within the ZIM program (Zentrales Innovationsprogramm Mittelstand), funded by the Federal Ministry for Economic Affairs and Energy under grant no. VP2194511AB4.

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Diodenlasersysteme, die Pikosekunden-Pulse im Frequenzbereich zwischen kHz und MHz im Leistungsbereich von einigen 10 W erzeugen, sind für eine Vielzahl von Anwendungen interessant. Dazu zählen etwa LIDAR, Metrologie, Medizin, Spektroskopie und Seed-Systeme für die Materialbearbeitung. 1 - 20 ps Pulse werden mittels Modenkopplung bei GHz-Folgefrequenz erzeugt. Pulse mit kontinuierlicher Variation der Pulsbreite von 250 ps bis zu einigen ns können nur durch „Ausschneiden“ (Pulsgating) aus einem CW-Laserstrahl generiert werden.

Im FBH wurde als Weltneuheit eine kompakte Laserquelle entwickelt, die zwischen Modenkopplung und Pulsgating geschaltet werden kann und optische Pulse im gesamten ps-Bereich erzeugt. Sie besteht aus einem Mehrsektions-Oszillator, der sowohl ps-Pulse im GHz Bereich als auch Gleichlicht erzeugen kann. Mittels monolithisch integriertem, ultraschnellem optischem Tor und Verstärker können sowohl Pulse aus einem Impulszug selektiert als auch ausgeschnitten werden. Die 20 W ps-Laserquelle ist auf einer 5 x 4 cm^2 optischen Mikrobank integriert.

Shifted Excitation Resonance Raman Difference Spectroscopy (SERRDS) system for medical investigation on skin and its application in clinical trials

Carotenes in human skin play an important role as biomarkers. Their concentration in skin could be an indication for point-of-care diagnostics as well as for therapeutic surveillance of certain treatments. Thus, monitoring the health status of human beings based on non-invasive skin measurements would offer new opportunities in medical diagnostics.

In oncology, the anti-oxidative status of the skin can be used to decide if chemotherapy is applicable, preventing the patient from side-effects like the hand-foot-syndrome. Carotenes like ß-carotene and lycopene show absorption bands in the blue-green spectral range, leading to a resonance enhancement of Raman lines. Although the Raman signals are enhanced they are often obscured by huge fluorescent signals and natural or artificial background light. To overcome this, a well-established spectroscopic method is shifted excitation resonance Raman difference spectroscopy (SERRDS), a straightforward, fast, and efficient tool to separate background interferences from the targeted Raman features.

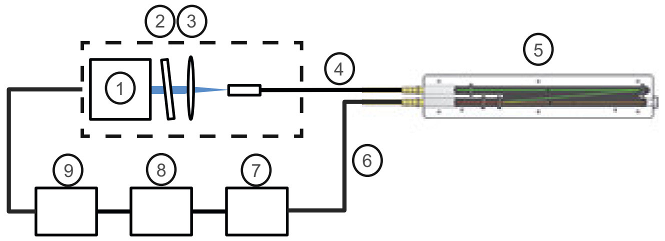

Fig. 1. Experimental setup consisting of beam combination for light sources emitting at 488 nm and 515 nm (1), NIR-filter (2), focusing lens (3), excitation fiber (4), SERRDS probe (5), detection fiber (6), spectrometer (7), PC (8), and current/temperature controller (9).

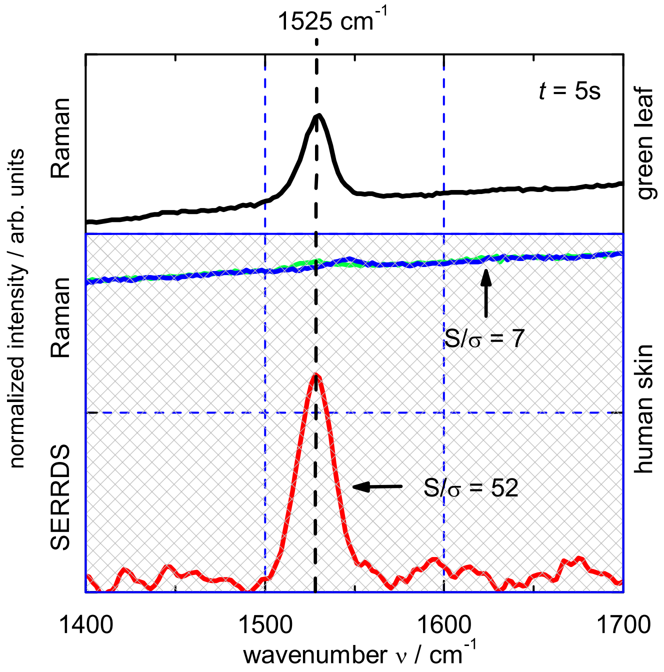

Fig. 2. Raman and SERRDS spectra of human skin in comparison with Raman spectrum of carotenes in a green leaf. SERRDS signals of human skin show a >7-fold increase in signal-to-noise ratio (SNR) vs. Raman signals.

To apply SERRDS, a light source is needed which provides alternatingly two slightly shifted laser emission lines. For optimized SERRDS signals, the spectral distance of both wavelengths should be close to the spectral width of the Raman signals, measured at full width at half maximum (FWHM). In our case this is 15 cm^{-1}. Concerning the output power, the excitation power allowed on human skin is limited to 2000 W/m^2 due to legal restrictions. Therefore, dual-wavelength lasers at 488 nm and 515 nm have been developed, offering a tuning range larger than 0.3 nm together with an output power of 20 mW. These diode laser based light sources were employed as key components together with a novel SERRDS probe, which is usable for medical applications and for the quantified detection of carotene concentrations below 0.05 nmol/g in human skin. The probe provides a spot diameter of 3 mm for homogenous excitation as well as detection and meets all safety regulations.

For clinical trial within the project *HautScan*, a mobile and miniaturized system – the scheme can be seen in Fig. 1 – was designed, comprising the in-house fabricated SERRDS probe and the dual-wavelength light sources. The system was constructed to be fully-automatically operated by clinical staff, meeting also the high requirements on the software package also developed by FBH. The light sources emitting at 488 nm and 514 nm were fixed on a heatsink, also comprising beam combination and fiber coupling. The light of the laser sources is transferred to the probe using a fiber with a core diameter of 50 µm. The probe contains all optical elements needed for excitation and detection and has a size of only 150 mm x 27 mm x 12 mm. This includes optics to enlarge the beam for excitation as well as optics to collect the backscattered light, short-pass and long-pass filters to eliminate fiber Raman signals and to block the excitation wavelength in the detection path. A sapphire glass window protects the inner components and makes the SERRDS probe suitable for disinfection which is indispensable in this context. The Raman signals are collected with a 200 µm fiber and transferred to a spectrometer.

Fig. 3. In-vivo SERRDS system applied at Helios clinic Bad Saarow. The system consists of spectrometer, current source, light sources in an aluminum case, and laptop (from bottom to top).

Before applying the system for in-vivo measurements on human skin, it was tested and calibrated using skin phantoms with well-defined ß-carotene concentrations at Charité Berlin. The power of the 488 nm excitation light source at the sample at wavelength λ_1 is 9.2 mW and at λ_2 it is 9.0 mW, respectively. The wavelength difference was adapted to the FWHM of the sample under study. A spectral distance of 15 cm^{-1} was adjusted with λ_1 = 487.20 nm and λ_1 = 487.57 nm in order to match the width of the carotene Raman signal. The spectral linewidth of both wavelengths is below 7 pm (0.3 cm^{-1}). Five spectra were recorded at each wavelength with 5 s integration time. By testing the skin samples we identified the limit of detection (LOD) for ß-carotene in human skin to be 0.05 nmol/g. This value is below the average value of healthy persons ranging around 0.4 nmol/g.

The clinical trial comprised the spectroscopic investigation of 20 healthy volunteers and 20 patients suffering from cancer. Measurements on the patients were done before and after chemotherapy to investigate changes in spectroscopic characteristics on the skin. The system was successfully applied on human skin, and we demonstrated an improvement for SERRDS in comparison to Raman for the signal-to-noise ratio (SNR) for Raman signals of carotenes at 1525 cm^{-1} (Fig. 2). For the first time, SERRDS measurements were performed during a clinical trial in order to investigate spectroscopic characteristics of human skin in the course of treatment with chemotherapy. The summarizing evaluation of the data is ongoing for the Charité and the FBH. The system utilized at Helios clinic in Bad Saarow is shown in Fig. 3.

This work was realized within the *HautScan* project funded by the Einstein-Stiftung under contract A-2011-88. The clinical trial was organized and realized together with FBH and Charité Berlin.

In der Onkologie können Karotinoide als Kriterium für die Anwendbarkeit bestimmter Chemotherapeutika genutzt werden. Ziel ist es dabei, Patienten vor den Nebenwirkungen einer Chemotherapie wie dem Hand-Fuß-Syndrom besser zu schützen. Karotinoide lassen sich im grün-blauen Spektralbereich resonant anregen, wodurch sich die Intensität des Raman-Signals verstärkt. Um die noch immer um mehrere Größenordnungen stärkere Fluoreszenz vom Raman-Signal zu trennen, wird SERRDS als etablierte Methode verwendet. Am Ferdinand-Braun-Institut wurde im Forschungsprojekt *HautScan* ein Gesamtsystem aufgebaut, welches die Anforderungen für Raman-Messungen an menschlicher Haut in einer klinischen Umgebung erfüllt. Es besteht aus Lichtquellen, emittierend bei 488 nm bzw. 515 nm, und einer handlichen SERRDS-Optode. Das System wurde in enger Zusammenarbeit mit der Charité erfolgreich getestet und im Rahmen einer klinischen Studie an krebskranken Patienten erprobt.

Publications

M. Braune, M. Maiwald, B. Eppich, O. Brox, A. Ginolas, B. Sumpf, G. Tränkle, "Design and realization of a miniaturized DFB diode laser based SHG light source with a 2 nm tunable emission at 488 nm", IEEE Trans. Compon. Packag. Manuf. Technol., vol. 7, no. 5, pp. 720-725 (2017).

M. Braune, M. Maiwald, B. Sumpf, G. Tränkle, "2 nm continuously tunable 488 nm micro-integrated diode laser based SHG light source for Raman spectroscopy", Proc. SPIE 9731, Photonics West, San Francisco, USA, 973116 (2016).

Highly brilliant laser sources for yellow light in bio-medicine

Laser sources emitting light at 589 nm are key components for many applications including high-resolution spectroscopy, optical traps for sodium atom cooling, LIDAR, flow cytometry and medical treatment in ophthalmology and dermatology. However, currently available laser sources lack direct modulation capability, suffer from low efficiency, and are usually fixed in their wavelength.

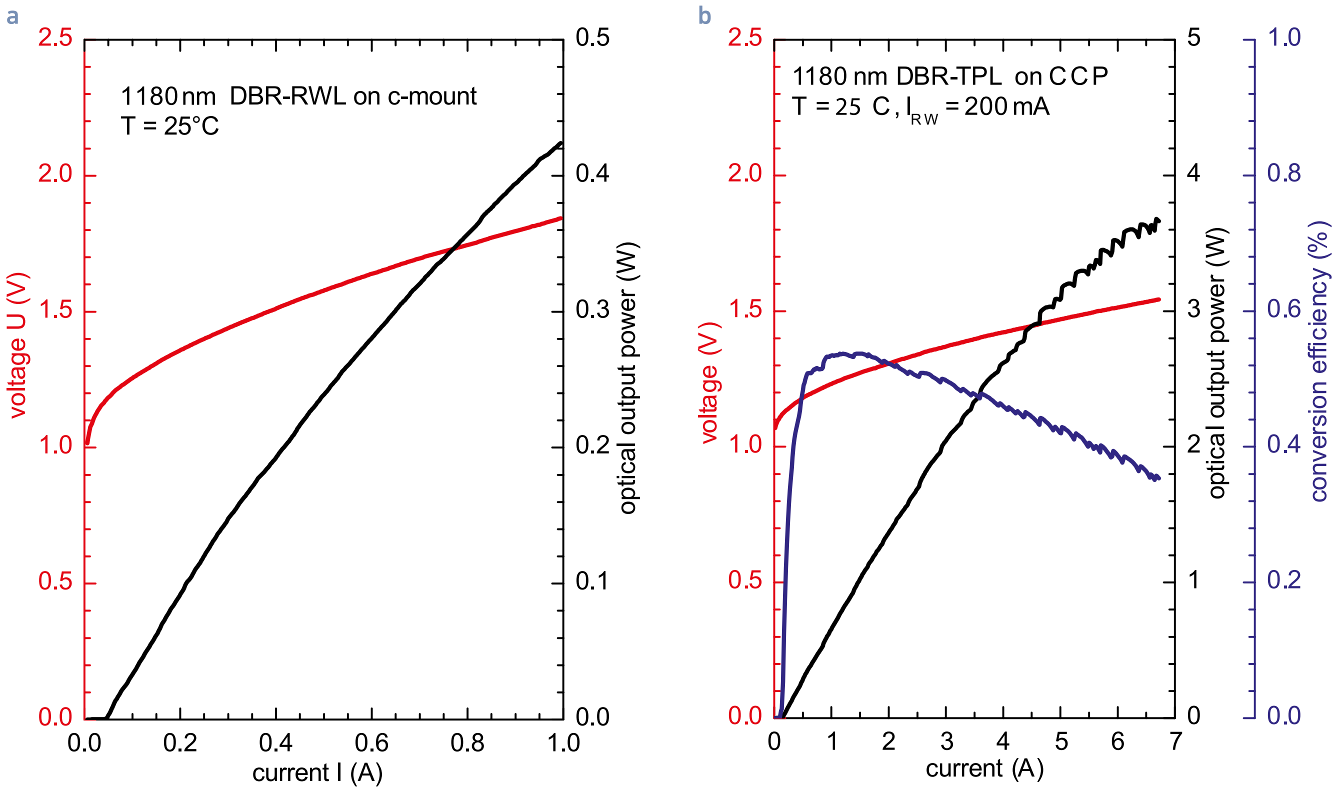

Fig. 1. Power-current-voltage characteristics at 25°C of a DBR-RWL (a) and of a DBR-TPL (b).

Semiconductor-based laser sources, developed within the BMBF-funded Yellow project are opening a way to eliminate these restrictions. They are the basis for laser modules delivering the required performance parameters. Due to their compact size – they are only as big as a matchbox – they also enable mobile applications. With them, equipment becomes transportable, examinations can be executed in situ, and results are thus available much faster.

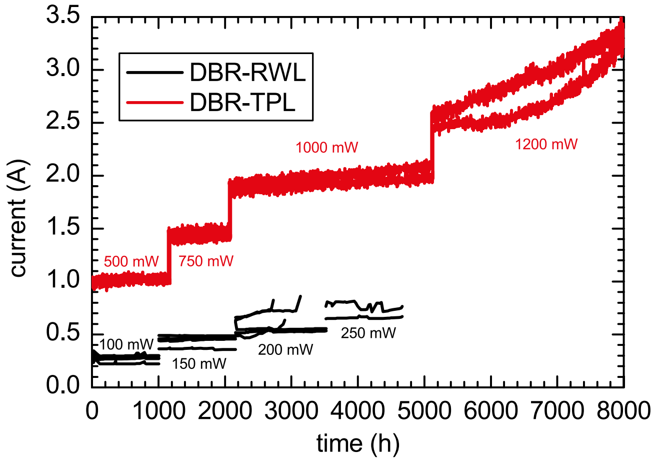

Fig. 2. Lifetime transients of DBR-RWLs (black) and DBR-TPLs (red) emitting near 1180 nm at constant power.

As direct-emitting laser diodes at 589 nm are currently not available, the FBH uses the concept of frequency doubling of newly developed diode lasers at 1178 nm. The realization is quite demanding, since the high indium content in the $In_xGa_{1-x}As$ quantum wells (QW) leads to high compressive strain. For emission wavelengths beyond 1100 nm, single QWs approach the theoretical critical thickness for the formation of dislocation lines according to the Matthews-Blakeslee's model. As such dislocations lead to rapid degradation of laser diodes it is necessary to optimize the growth process and the design of the laser structures, in order to accommodate the high strain and thus avoid defect formation. The FBH successfully mastered this challenge: The new lasers feature highly strained InGaAs quantum wells and higher order surface gratings as Bragg reflectors for a stabilized emission wavelength around 1178 nm. Electrical heaters next to the DBR grating enable fine tuning of the emission wavelength without any moving parts.

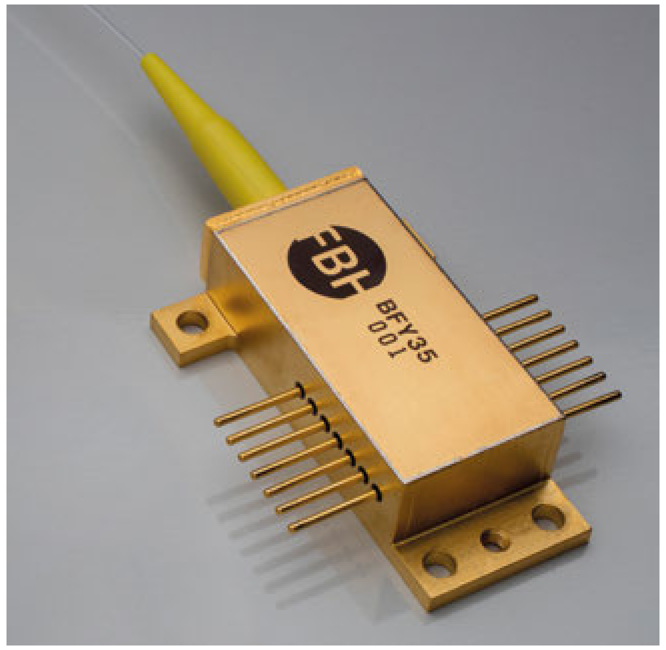

Fig. 3. Micro-module emitting in the yellow spectral range based on a DBR-TPL as pump source and an RW crystal for SHG.

These new monolithic distributed Bragg reflector ridge waveguide diode lasers (DBR-RWL) at 1178 nm emit high optical output power of more than 300 mW and a nearly diffraction-limited beam. Fig. 1(a) shows the power-current-voltage characteristics of such a laser. These laser sources emit a single longitudinal mode with side-mode suppression ratios of more than 40 dB [1, 3]. They are highly reliable as can be seen in the lifetime test data in Fig. 2. Due to their high brilliance, tunability, and small size these laser diodes are well suited for compact laser modules at 589 nm using second-harmonic generation (SHG). In experiments on an optical bench with PPMgO:LN ridge waveguide (RW) crystals an optical output power of 74.8 mW at 589 nm using 306 mW pump power has been achieved.

In order to further increase the optical output power, the FBH developed monolithic distributed Bragg reflector tapered diode lasers (DBR-TPL) emitting at 1178 nm. The mounted lasers feature an output power of more than 2 W and a conversion efficiency of more than 40 %, see Fig. 1(b). The DBR-TPLs can be operated at output powers exceeding 1 W for more than 3000 h, as shown in Fig. 2. This laser emits into a single longitudinal mode at 1177.9 nm and has an excellent beam quality, providing 90 % of the power in the central lobe. The central wavelength is tunable by 3 nm using the DBR-grating heaters [4]. More than 860 mW in the yellow spectral range have been achieved on an optical bench with these DBR-TPLs as pump source [2].

The first micro-module integrating a DBR-TPL as pump source and an RW crystal for SHG can be seen in Fig. 3. This concept allows miniaturizing existing laser systems for bio-analytics and spectroscopy in the yellow-green spectral region.

This work was funded by the Federal Ministry of Education and Research (BMBF) of the Federal Republic of Germany under contract 03IPT613Y.

In der Medizin oder bei umweltanalytischen Messverfahren werden Laserquellen genutzt, die Licht bei 589 nm emittieren. Für viele Anwendungen reichen jedoch Effizienz, Modulationsgeschwindigkeit oder Durchstimmbarkeit der derzeitigen Laser nicht aus. Abhilfe könnten miniaturisierte halbleiterbasierte Laserquellen aus dem FBH schaffen. Dank deren kompakter Größe werden die Geräte zudem kleiner, leichter und somit transportabel. Allerdings sind direkt emittierende Laserdioden bei 589 nm derzeit nicht verfügbar. Daher verfolgt das FBH den Ansatz der Frequenzverdopplung. Das Institut hat hierzu sowohl Rippenwellenleiterdioden als auch Trapezlaserdioden mit 1178 nm Wellenlänge entwickelt, die auf InGaAs-Quantengräben mit integrierten Oberflächengittern basieren. Diese zeichnen sich durch eine hohe Ausgangsleistung von bis zu 3 W bei beugungsbegrenzter sowie spektral schmalbandiger Emission aus. Damit sind die Laser ideal für die direkte Frequenzverdopplung geeignet. Es konnten damit bis 0,86 W im gelben Spektralbereich demonstriert werden.

Publications

[1] K. Paschke, G. Blume, A. Ginolas, J. Hofmann, D. Feise, W. John, N. Werner, F. Bugge, "1180nm DBR-ridge waveguide lasers with strain compensation layers in the active region for lifetime improvement", Proc. International Semiconductor Laser Conference ISLC (2016).

[2] R. Bege, D. Jedrzejczyk, G. Blume, J. Hofmann, D. Feise, K. Paschke, G. Tränkle, "Watt-level second-harmonic generation at 589 nm with a PPMgO:LN ridge waveguide crystal pumped by a DBR tapered diode laser", Opt. Lett. 41, 7 (2016).

[3] K. Paschke, F. Bugge, G. Blume, D. Feise, G. Erbert, "High power diode lasers at 1178 nm with high beam quality and narrow spectra", Opt. Lett. 40, 100 (2015).

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Laser sources emitting around 577 nm for ophthalmology

Laser sources are widely used in ophthalmology, including treatment of retinal detachment, a frequent ophthalmic attendant symptom of diabetes (diabetic retinopathy). Over the course of this disease, vascular leakage in the retina causes loss of visual acuity or color vision and – without treatment – even blindness. By means of photothermolysis using laser radiation, blood coagulates in the diseased vasculatures, which are replaced by healthy blood vessels during the healing process. Laser radiation around 577 nm is favored, since blood (oxyhemoglobin) shows a distinct absorption peak at this wavelength, and scattering at melanin in the epidermis is declined. Thus, the necessary power for eye treatment can be reduced, alleviating adverse side effects like retinal scarring. Additionally, pulsed operation of the laser source constrains the treatment on blood vessels. For this purpose, pulses shorter than the thermal vascular relaxation down to 10 ms are applied. Thus, an appropriate laser source for sufficient retinal treatment requires an optical output power between 300 mW and 1 W, a modulation ranging from 10 ms to continuous wave, and a high coherence to focus the beam on small spots at the retina.

In the clinical daily life, hand-hold devices with ideally maintenance-free operation are requested. Diode lasers would meet these requirements convincing with their compactness and effectivity in addition. Since no direct emitting diode lasers are available at the targeted wavelength, only frequency doubling of diode laser radiation in the near infrared can be employed by means of a nonlinear crystal in single-pass configuration to keep the setup compact and less complex. In order to achieve optical output powers up to 1 W around 577 nm, the diode laser has to provide several watts of pump power around 1154 nm. However, only quantum dot lasers with output powers of a few hundred milliwatts have been demonstrated at this wavelength. At the FBH, epitaxial laser structures have recently been developed comprising a highly compressively strained InGaAs quantum well. DBR tapered diode lasers are processed from this structure emitting radiation up to 3.0 W at 1156.9 nm (see Fig. 1). A good beam quality in the slow axis ($M_{1/e^2}^2 = 1.3$) and a narrow-lined emission suitable for frequency doubling are preserved at this power level. Despite high strain in the active layer, long lifetimes of more than 6.000 h are demonstrated in step-stress tests (see inset in Fig. 1).

In a bench-top experiment, frequency doubled radiation up to 0.86 W is proved by means of a lithium niobate ridge-waveguide crystal. The crystal is pumped by an effective maximum power of 2.0 W (see Fig. 2). The spectral width is about 0.23 pm (see inset Fig. 2); the beam quality factor M_s^2 is determined to 1.2 in both the fast and slow axes.

First modulation tests have been realized with modules offering an optical output power around 0.3 W at 561 nm. The modules comprise a master-oscillator power-amplifier setup as pump source and a bulk or a planar lithium niobate crystal (see Fig. 3). Modulated frequency doubled output powers are achieved with pulses as short as 1 ms (see Fig. 4). This technology of pulsed operation is capable of being transferred to modules emitting at 577 nm.

We acknowledge the Federal Ministry of Education and Research (BMBF) for funding within the InnoProfile initiative „Unternehmen Region" (contract 03IPT613Y)

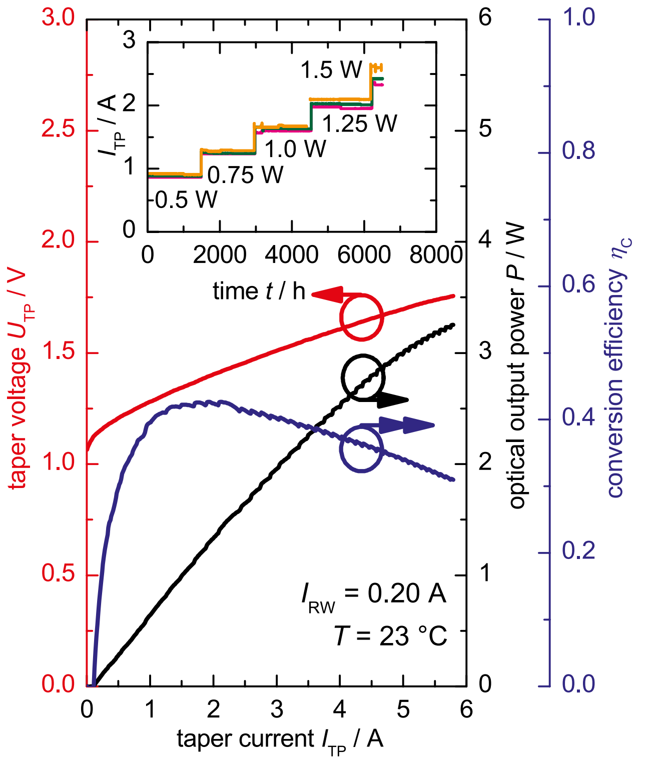

Fig. 1. Characteristics of a DBR tapered diode laser vs. taper current. Inset: lifetime data without failure of three DBR tapered diode lasers under investigation.

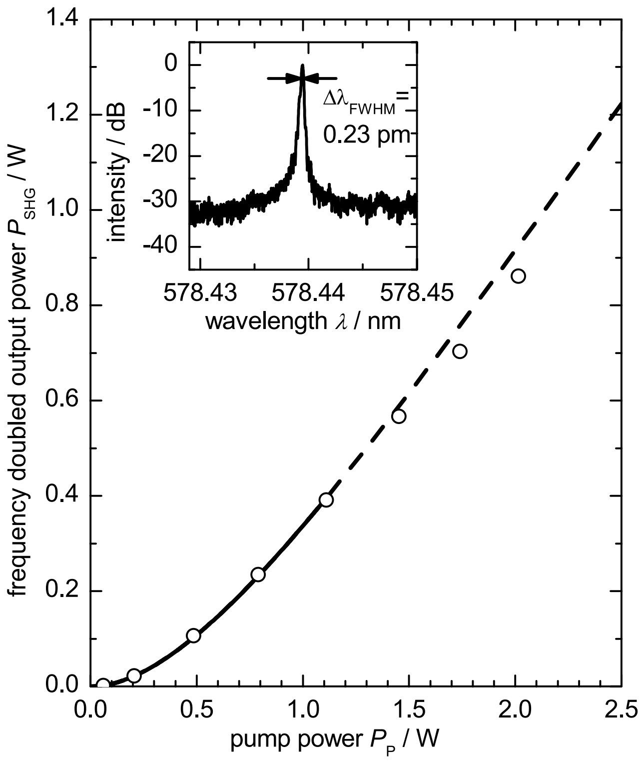

Fig. 2. Frequency doubled output power vs. pump power. Inset: spectrum at the highest output power.

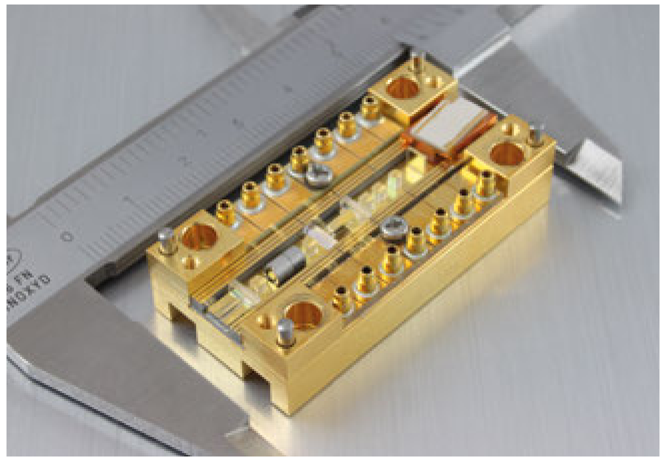

Fig. 3. Module comprising a master-oscillator power-amplifier setup and a nonlinear planar crystal for pulsed operation at 561 nm.

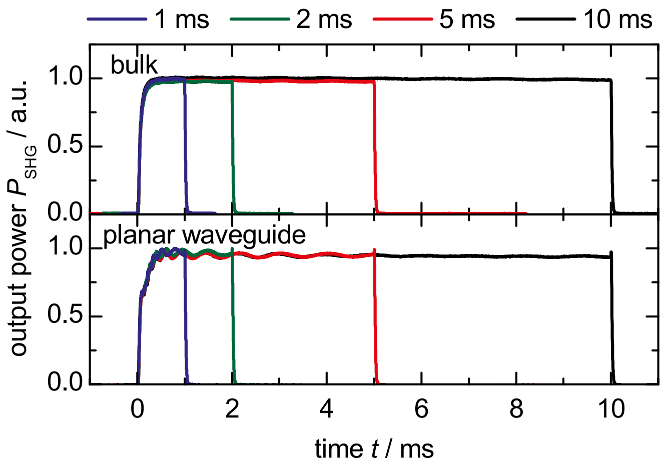

Fig. 4. Normalized frequency doubled output power for modules based on a master-oscillator power-amplifier and a nonlinear crystal (bulk and planar) at various pulse durations.

Bei der Behandlung von Netzhautablösungen (Retinopathie) werden Laserquellen zur Fotokoagulation in krankhaften Blutgefäßen benötigt. Dafür eignet sich der Wellenlängenbereich um 577 nm besonders gut, da die Absorption des Blutes hier erhöht ist. Bei gepulstem Betrieb bis etwa 1 W optischer Ausgangsleistung kann die Therapie auf die zu behandelnden Blutgefäße beschränkt werden und schädigt so kein umliegendes, gesundes Gewebe. Das FBH erreicht die erforderliche Wellenlänge mittels Frequenzverdopplung von Diodenlaserstrahlung bei 1154 nm. Dabei nutzt das Institut einen kompakten Aufbau, der die Herstellung wartungsarmer, handlicher Geräte für den klinischen Gebrauch ermöglicht. Am FBH konnten hierfür erstmals leistungsfähige DBR-Trapezlaser mit einer optischen Ausgangsleistung > 3 W (Fig. 1) realisiert werden, die auf einem stark verspannten Quantenfilm basieren und Lebensdauern von mehr als 6.000 h bieten (Inset Fig. 1). Bei der Frequenzverdopplung mittels eines Stegwellenleiterkristalls wurde eine beugungsbegrenzte Leistung von 0,86 W bei 577 nm mit einer Linienbreite von 0,23 pm erreicht (Fig. 3). Für Mikromodule mit einer Emission bei 561 nm konnten bereits gepulste Anwendungen bis hin zu einer Pulsdauer von 1 ms gezeigt werden. Diese Technologie lässt sich auf Module mit einer Emission bei 577 nm übertragen.

Publications

R. Bege, G. Blume, D. Jedrzejczyk, K. Paschke, D. Feise, J. Hofmann, F. Bugge, G. Tränkle, "Yellow laser emission at 578 nm by frequency doubling with diode lasers of high radiance at 1156 nm", Appl. Phys. B, 123 : 109 (2017).

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Micro-integrated extended cavity diode laser master oscillator power amplifier module for precision spectroscopy of iodine in space

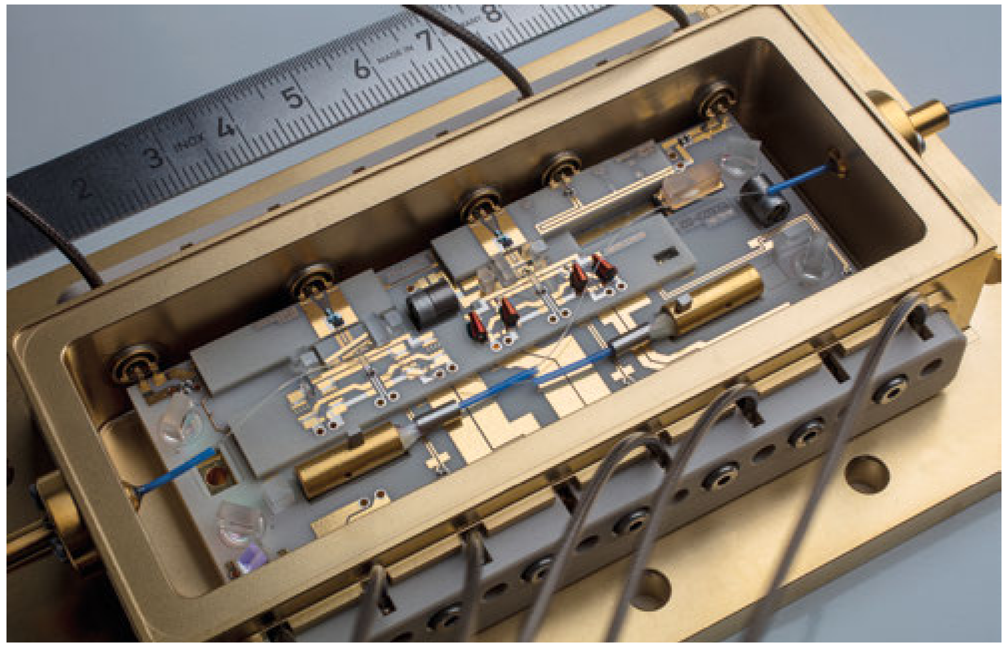

Fig. 1. Photograph of an extended cavity diode laser master oscillator power amplifier module.

One approach to stabilize lasers of optical frequency is to apply spectroscopic methods in order to lock them to optical transitions of atoms or molecules. The most appropriate species is determined, amongst others, by the frequency of the laser to be stabilized. For example, the rubidium D_2 transition is often used for lasers emitting at 384.231 THz (780 nm). Using atoms or molecules for frequency stabilization is advantageous, since they provide an absolute frequency reference that is not subject to aging or long-term frequency drifts caused, for example, by temperature changes. Therefore, such frequency references are particularly suitable for experiments where ambient conditions are constantly changing with time and which require long measurement times. One field of application is in optical quantum sensors operated in space or in the field, e.g., sensors for the observation of climate changes or for inertial navigation. This kind of environment demands for compact and portable frequency references. Another application is related to gravitational wave detection, where ultra stable lasers are required to implement extremely sensitive optical interferometers.

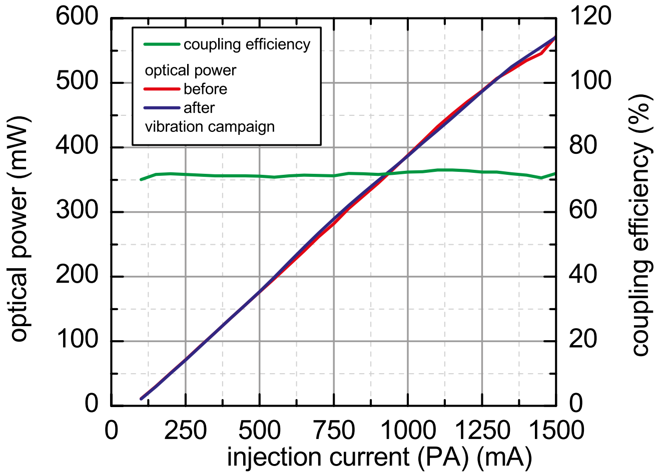

Fig. 2. Optical output power and coupling efficiency at the main port single-mode fiber output as a function of PA injection current before and after a vibrational stress test campaign.

FBH has micro-integrated an extended cavity diode laser master oscillator power amplifier (ECDL-MOPA) laser module emitting at 281.630 THz (1064,490 nm) (Fig. 1). This laser will be part of an absolute frequency reference based on molecular iodine – design and system integration of which will be carried out by Humboldt-Universität zu Berlin. Iodine provides an optical hyperfine transition (R(56)32-0 a_{10}) close to 532 nm. To address this transition, the ECDL-MOPA output optical field has to be frequency doubled. Due to the narrow natural linewidth of only 144 kHz, the iodine reference provides very low frequency instabilities. Further, the absolute frequency can be reproduced within a few kHz. The overall system is scheduled to be operated onboard a sounding rocket at the end of 2017 – an important step towards qualification of iodine-based frequency references for application in space. To demonstrate the performance of the reference its optical frequency will be compared to that of a microwave reference oscillator by means of an optical frequency comb during flight.

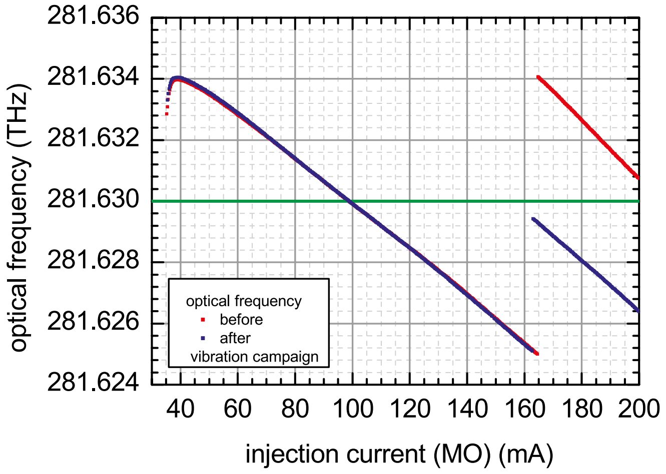

Fig. 3. Continuously frequency tuning of the laser module by tuning the MO injection current.

FBH's ECDL-MOPA is based on a versatile technology platform which facilitates integration of any two chips, either active (e.g. laser or amplifier) or passive (e.g. phase modulator), into a single laser module. The module contains a micro-optical bench (MioB) with a footprint of 80 x 30 mm^2, consisting of structured aluminum nitride substrates. It is encapsulated into a Kovar housing which can be seam-welded with a lid. The MioB accommodates semiconductor chips, micro-optics, electronics, and fiber coupling assemblies for coupling into single-mode, polarization maintaining optical fibers. The integration technology utilizes manufacturing processes and materials that are either space qualified or space compatible. All components are soldered or adhesively bonded. The laser module features a mass of 750 g and a form factor of 125 x 75 x 22.5 mm^3.

The laser module designed to serve as the local oscillator of the absolute frequency reference consists of a narrow linewidth ECDL master oscillator and a power amplifier chip. A volume holographic Bragg grating (VHBG) and the front facet of a 2 mm long ridge-waveguide laser chip form the cavity of the ECDL. The main output of the ECDL is collimated by two cylinder lenses and directed through a micro-optical isolator. Then, the collimated laser light is injected into a tilted, 6 mm long, ridge-waveguide power amplifier by a second pair of cylinder lenses. The output of the power amplifier is collimated by an aspheric lens, passed through a thin film polarizer, and coupled into a polarization maintaining, single-mode optical fiber. The auxiliary output of the ECDL is passed through an optical isolator, collimated by an aspheric lens, and coupled into a second polarization maintaining, single-mode optical fiber.

The ECDL-MOPA provides an optical power (ex fiber) of 570 mW at a frequency of 281.630 THz when operated at a MO injection current of 97.0 mA, a PA injection current of 1500 mA, a MioB temperature of 27.7 °C, and a VHBG temperature of 25.0 °C (Fig. 2). Such high output power enables frequency doubling even for frequency doubling stages with low conversion efficiencies. At this working point the linewidth of the laser was determined to be 26 kHz (FWHM, 1 ms time scale). The Lorentzian FWHM linewidth derived from the white noise floor of the frequency noise power spectrum was determined to be as small as 584 Hz. By sweeping the injection current with a sensitivity of 74 MHz/mA (Fig. 3) the ECDL can be continuously frequency-tuned. Its tuning range is limited by the free spectral range of the laser. Coarse tuning is provided by thermal tuning of the VHBG at 2.8 GHz/K. The side mode suppression ratio (SMSR) exceeds 45 dB. This module does not only provide excellent electro-optical performance, it has also successfully passed a random vibration test at 8.8 g_{rms}, simulating the launch of a sounding rocket.

This work is supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy under grant numbers 50WM1141, 50WM1545, and 50WM1646.

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Doppler-freie spektroskopische Verfahren, die optische Übergänge in Atomen oder Molekülen nutzen, eignen sich besonders gut für die optische Frequenzstabilisierung von Lasern. Aufgrund der schmalen Linienbreite solcher Übergänge bieten derart stabilisierte Laser eine exakt definierte Mittenfrequenz und eine geringe Frequenzinstabilität. Sie können daher als absolute optische Frequenzreferenz verwendet werden. Im Rahmen eines DLR-finanzierten Projektes hat das Ferdinand-Braun-Institut einen Extended Cavity Diode Laser Master Oscillator Power Amplifier (ECDL-MOPA) für die Spektroskopie von Iod entwickelt, mikro-integriert und elektro-optisch charakterisiert. Der ECDL-MOPA emittiert bei 1064 nm eine Leistung von 570 mW aus einer polarisationserhaltenden Singlemode-Faser. Das vom FBH entwickelte Lasermodul wird von der Humboldt-Universität zu Berlin zu einem Lasersystem mit absoluter Frequenzreferenz basierend auf Iod aufgebaut. Die Spektroskopie des Iod-Übergangs bei 532 nm wird durch Frequenzverdopplung der Strahlung erreicht. Ende 2017 soll das Gesamtsystem auf einer Höhenforschungsrakete getestet werden und den Weg für weltraumbasierte absolute Frequenzreferenzen bereiten, die auf der Spektroskopie an Atomen oder Molekülen basieren.

Precision spectroscopy with potassium and rubidium in space

According to Albert Einstein's theory of relativity, all bodies in a vacuum regardless of their properties are accelerated by the Earth's gravity at the same rate. Under the conditions of microgravity very precise measurements can be carried out over long measurement intervals to test this principle of equivalence. For the first precision measurements in space with cold atoms, potassium and rubidium are suitable candidates. To prepare these measurements, two experiments were conducted at the same time onboard a sounding rocket launched in January 2016. Both technology demonstrator experiments, KALEXUS and FOKUS, used different types of lasers developed by the FBH.

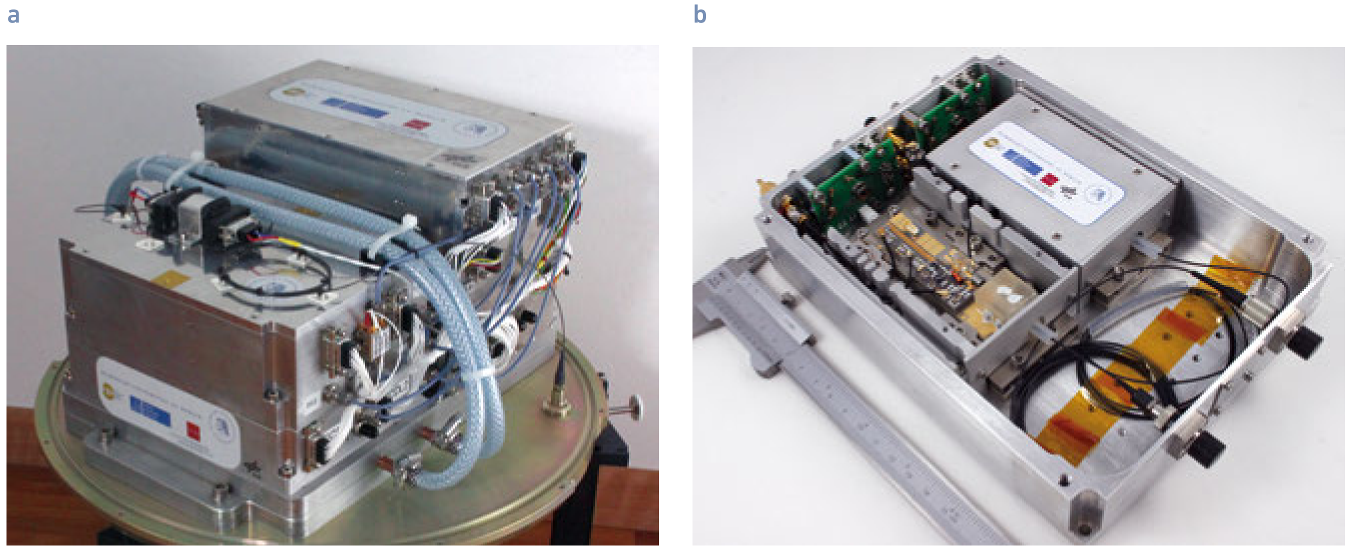

Fig. 1. KALEXUS experimental payload (a) and laser unit (b) with two micro-integrated ECDLs.

The KALEXUS experimental payload shown in Fig. 1(a) consists of three physical and functional units: lasers, potassium spectroscopy unit, and electronics. The laser unit depicted in Fig. 1(b) is equipped with two hybrid micro-integrated diode laser modules. These laser modules are based on the extended cavity diode laser (ECDL) concept. They feature a short term (10 µs) linewidth of less than 100 kHz and a white noise floor of the frequency noise power spectral density (PSD) that corresponds to a Lorentzian linewidth of a few kHz. This spectrally narrow emission is a key requirement for a laser module to be used for precision spectroscopy of potassium atoms, in order to carry out a test of the equivalence principle. For deployment in space, the diode laser modules ultimately have to withstand the mechanical loads during a rocket launch with accelerations of up to 15 *g* and need to function reliably in space. In microgravity, onboard the sounding rocket TEXUS 53, the KALEXUS experiment successfully demonstrated a major prerequisite for future precision measurements in space: the autonomous frequency stabilization of the laser modules. This was achieved by means of Doppler-free frequency modulation spectroscopy (FMS) of potassium (Fig. 2).

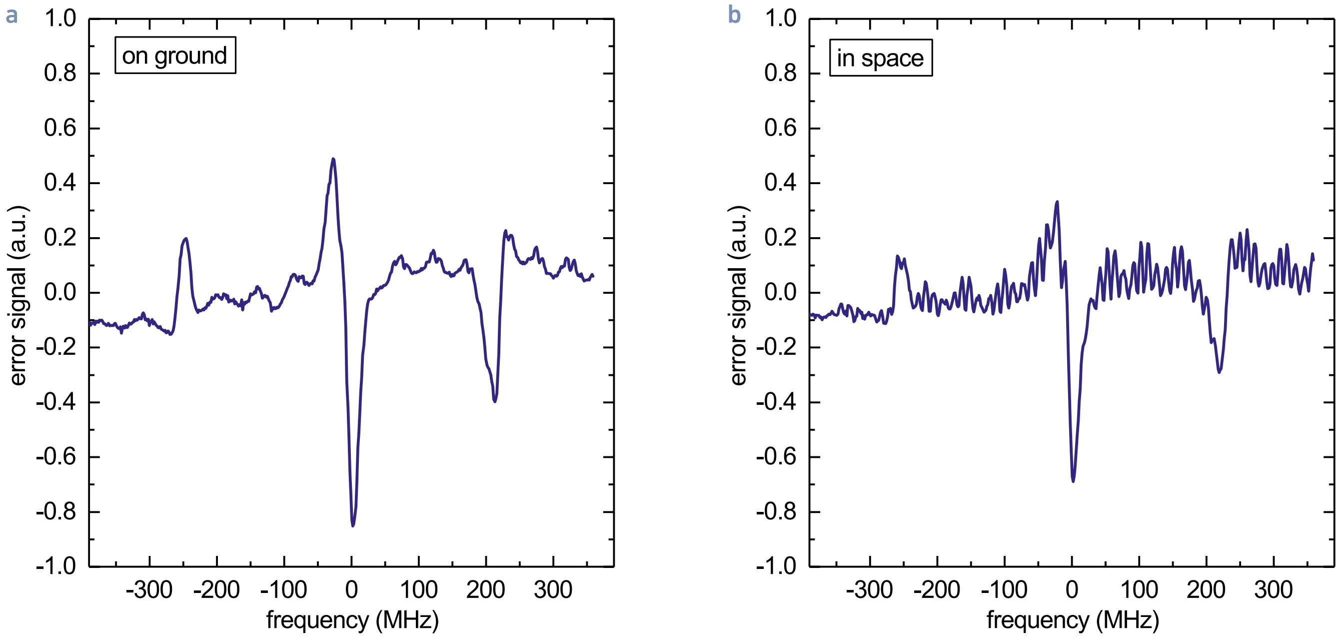

Fig. 2. Potassium FMS signal recorded by the KALEXUS experiment on ground (a) and in space (b).

The FOKUS experiment was a so-called re-flight of an upgraded version of a previously launched experiment. Besides the main experimental payload – a frequency comb – FOKUS contains a rubidium laser spectroscopy module, the centerpiece of which is a hybrid micro-integrated diode laser module with a distributed feedback (DFB) diode laser emitting light at a wavelength of 780 nm. This laser features a frequency noise and a linewidth that are by about one order of magnitude larger than the corresponding values of KALEXUS ECDLs. However, its monolithic structure makes it less prone to mechanical stress and interference. As a consequence, the FOKUS laser module remained frequency-stabilized not only in microgravity, but also during the boost phase of the sounding rocket.

Finally, both diode laser module concepts, DFB laser and ECDL, successfully proved their suitability for future sounding rocket missions.

This work was supported by the German Aerospace Center (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant numbers 50WM0934, 50WM0937-0940, 50WM123-1240, 50WM1343, and 50WM1345.

Gemäß Einsteins Relativitätstheorie werden alle Körper gleich stark im Gravitationsfeld der Erde beschleunigt. Dieses Äquivalenzprinzip kann in Mikrogravitation, der annähernden Schwerelosigkeit, durch präzise Experimente mit langen Messzeiten überprüft werden. Für die ersten derartigen Tests sind Experimente mit Kalium- (767 nm) und Rubidium-Atomen (780 nm) geplant. Vorbereitend dazu wurden im Januar 2016 zwei Experimente auf einer Höhenforschungsrakete durchgeführt, bei denen unter anderem zwei unterschiedliche Lasertechnologien (ECDL und DFB) mit Lasermodulen aus dem FBH verglichen wurden.

Im KALEXUS-Experiment wurde die autonome Frequenzstabilisierung von zwei ECDL-basierten hybrid-integrierten Lasermodulen auf einen atomaren Übergang von Kalium unter Weltraumbedingungen getestet. Im Rahmen des FOKUS-Experiments wurde die Stabilisierung eines DFB-basierten hybrid-integrierten Lasermoduls auf einen Rubidium-Übergang untersucht. Beide Laserkonzepte konnten ihre Eignung für zukünftige Präzisionsexperimente erfolgreich demonstrieren.

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Analyzing the degradation of UV LEDs using capacitance-voltage measurements

Ultraviolet light-emitting diodes (UV LEDs) with emission between 250 nm and 320 nm are promising devices for a variety of applications such as water purification, gas sensing, and UV curing. Meanwhile, AlGaN-based UV LEDs have been realized by a number of groups, covering almost the entire UV wavelength range. However, the reliability of such devices is still limiting their applicability and thus impeding widespread usage. To this day, the typical lifetimes of state of the art UV-B LEDs, for example, is restricted from a few 1,000 h to about 10,000 h at the most, which is much lower than those of GaN-based blue LEDs.

Within the Joint Lab GaN Optoelectronics of FBH and the Institute of Solid State Physics at TU Berlin, UV-B and UV-C LEDs with emission wavelengths of 310 nm and 265 nm have been developed. For advanced device development, which means increasing lifetime in this context, obtaining a deeper understanding of physical mechanisms causing stress-induced degradation is critical. In order to explore the degradation processes, the UV-B and UV-C LEDs were exposed to an accelerated aging for 200 hours at a constant current density of 140 A/cm^2 and different temperatures. It was found that the drop of the optical power is more pronounced for the UV-C LEDs compared to the UV-B LEDs. The degradation of UV-C LEDs also exhibited a much stronger temperature dependence. To better understand this discrepancy, the LEDs have been electro-optically analyzed before, during, and after stress.

The pn-junction of the LED creates a space charge region (SCR) whose width can be accessed by capacitance-voltage (CV) measurements. Comparing the capacitances before and after stress reveals information on the impact of temperature during stress, see Fig. 2. While for the UV-C LEDs the capacitance gets smaller, which can be attributed to an enlargement of the SCR, the capacitance of the UV-B LEDs increased for stress temperatures ≤ 60 °C. This contrasting behavior indicates that at least two different degradation mechanisms are prominent in these devices.

To learn more about stress-induced changes of the device capacitance, CV measurements of the UV-B LEDs at several points of time during aging were performed. It turned out that the capacitance increases mostly at the beginning of the aging process. This leads to the question where exactly the changed SCR is located within the heterostructure. Therefore, we developed a method to solely measure the p-side of the stressed device. This allowed us to separate effects of the p-side degradation from those of the pn-junction and the n-side of the LED heterostructure. Our investigations show, as can be seen in Fig. 3, that the initial increase in capacitance can be attributed to changes in the p-doped region of the AlGaN LED heterostructure, most likely due to activation of magnesium acceptors. The described method offers new insights into degradation processes of AlGaN-based UV LEDs. Especially the possibility to locate the changes in the LED heterostructure should enable a more specific approach to device optimization.

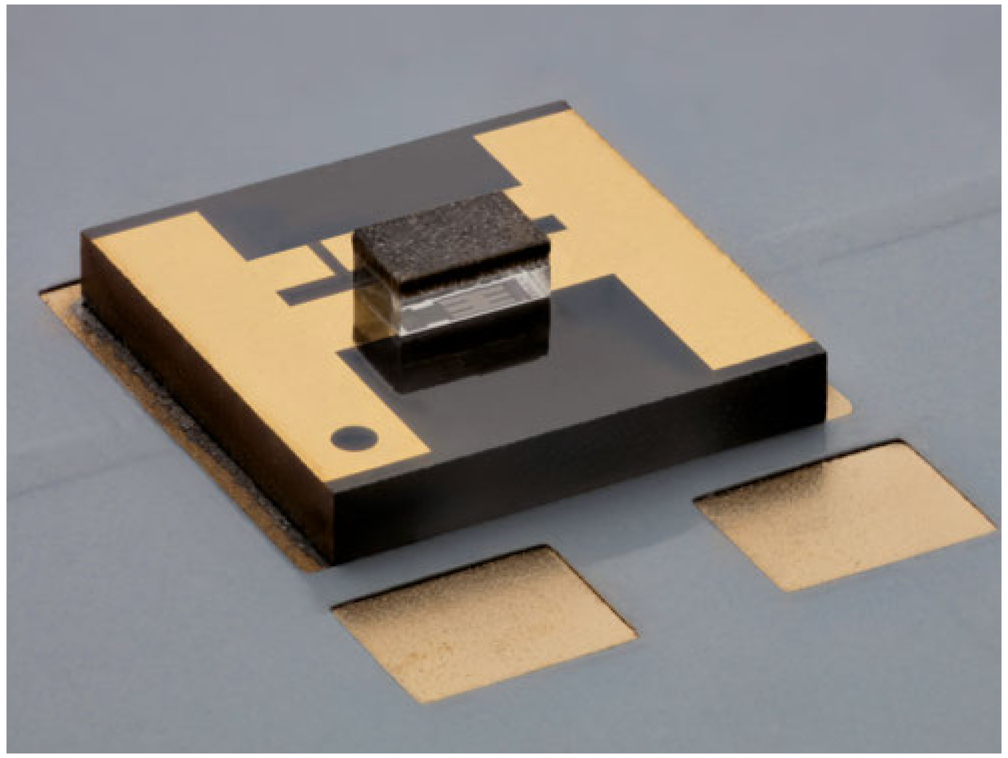

Fig. 1. Typical image of a flip-chip mounted UV LED on AlN submount.

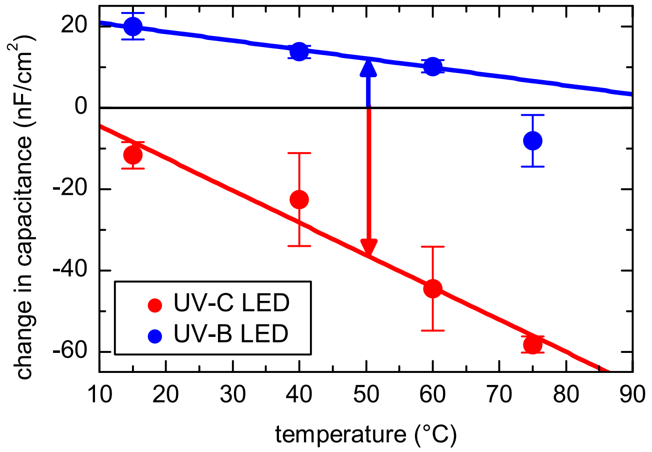

Fig. 2. Change in measured device capacitance due to a 200 h constant current stress as a function of heat sink temperature during stress.

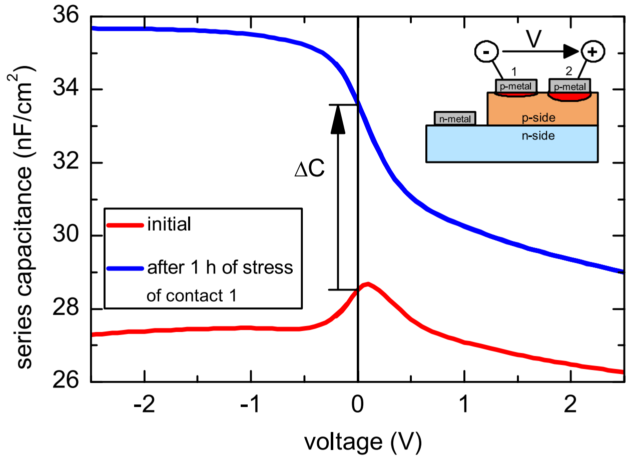

Fig. 3. Capacitance-voltage profiles of two p-contacts measured in series before (black) and after (red) constant current stress of the LED-structure underneath one of these contacts.

This work was partially supported by the German Federal Ministry of Education and Research (BMBF) through the consortia project *Advanced UV for Life* under contracts 03ZZ0105A and 03ZZ0105B. Further support was given by the Federal Ministry for Economic Affairs and Energy (BMWi) through the project *UV-Berlin* under contract 03EFCBE067 as well as by the Deutsche Forschungsgemeinschaft within the Collaborative Research Center “Semiconductor NanoPhotonics” (CRC 787).

AlGaN-basierte UV-LEDs mit Emissionswellenlängen im Bereich von 250 nm bis 320 nm sind vielversprechende Bauelemente für eine Vielfalt möglicher Anwendungsgebiete wie etwa Wasserentkeimung, UV-Aushärtung oder Gasdetektion. Allerdings begrenzt die Lebensdauer derzeit noch die Nutzbarkeit. Um die der Alterung zugrundeliegenden Prozesse zu untersuchen, hat das Joint Lab GaN-Optoelectronics – eine Kooperation von FBH und TU Berlin – beschleunigte Alterungstests an seinen LEDs durchgeführt. Kapazitäts-Spannungs-Messungen vor und nach der Alterung lieferten dabei Informationen über die Veränderung von Raumladungszonen innerhalb der LED-Heterostrukturen. Zudem war es durch eine speziell entwickelte Methode möglich, Effekte der p-seitigen Degradation von denen in anderen Bereichen des Bauelements zu separieren. Dadurch können insbesondere alterungsbedingte Änderungen lokalisiert werden – so lassen sich die Bauelemente künftig weiter optimieren.

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Deep-UV LEDs for nitrogen oxide gas sensing

Sensing of gases such as ammonia (NH_3), nitrogen oxide (NO), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) is of great interest for a wide range of applications including automotive, medical diagnostics, and environmental monitoring. Such gases exhibit strong and distinct absorption lines in the ultraviolet (UV) spectral range, e.g., NO near 226 nm. Principally, wavelengths in the UV-C range can be accessed by AlGaN-based light-emitting diodes (LEDs). These devices come along with advantages like adjustable wavelength, small sizes, low-voltage operation, and the possibility for fast on and off switching. Deep-UV LEDs are therefore suited for highly sensitive and selective gas monitoring systems, providing the opportunity to outperform many currently used systems based on chemical reactions.

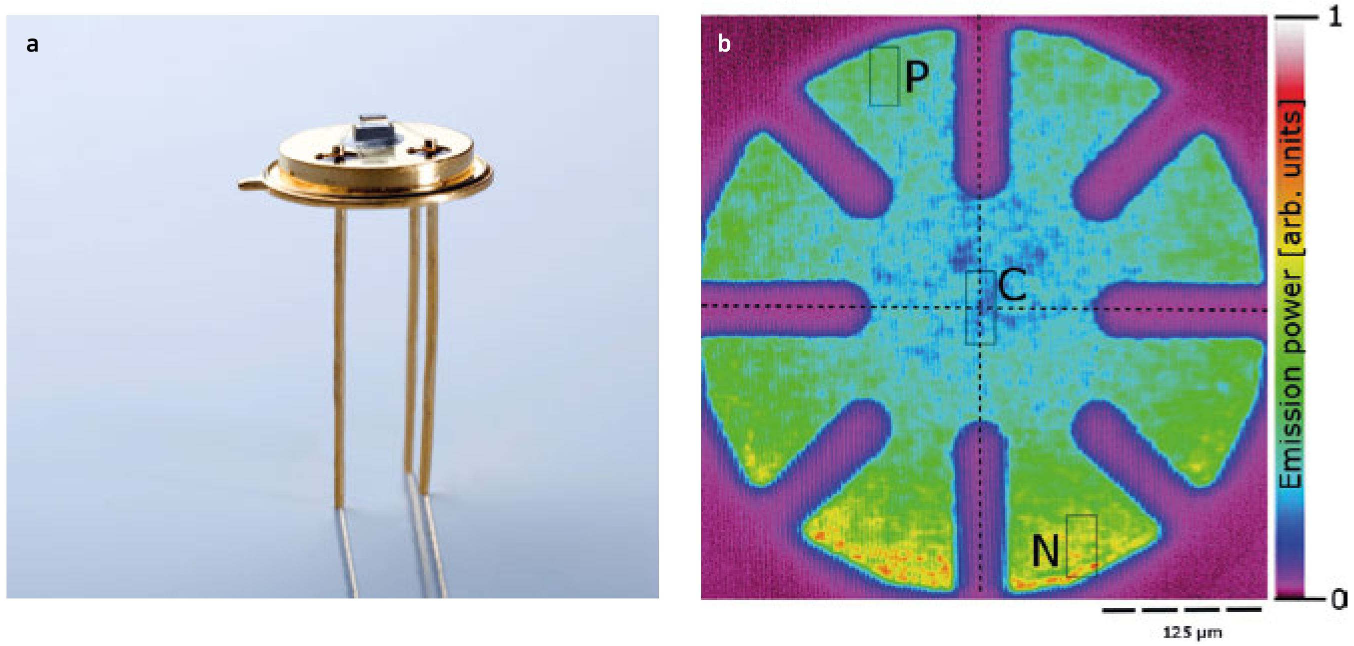

Fig. 1. (a) 232 nm LED chip mounted on AlN submount and TO header, (b) emission power distribution of the LED operated at a current of 20 mA.

UV LEDs emitting below 250 nm require AlGaN heterostructures with very high aluminum mole fractions exceeding 80 %. However, this results in low efficiencies and output powers, limited spectral purity, and fast degradation. Within a collaboration of the Ferdinand-Braun-Institut, Technische Universität Berlin and Universität Rostock, deep-UV LEDs emitting near 232 nm have been realized and successfully used to detect NO in the ppm range.

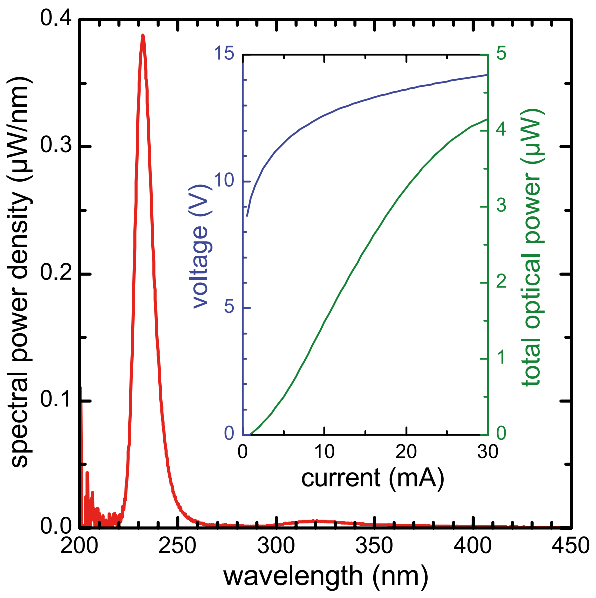

Fig. 2. Spectral power density of a 232 nm LED at 40 mA with a p-contact area of 0.1 mm², inset: P-I-V characteristics.

Design and fabrication process of the epitaxial heterostructure of the LEDs have been optimized in terms of high internal quantum efficiency, high charge carrier injection efficiency, and low series resistance. This included all aspects of materials development such as smooth AlN base layers with low dislocation density on sapphire substrates by epitaxial lateral overgrowth, silicon doping of the AlGaN current spreading layer, confinement in the quantum wells, magnesium doping, composition and thickness of the electron blocking layer as well as the hole injection layer. As a result, the quantum well emission power was strongly increased and the intensity ratio of the quantum well emission to parasitic emission at longer wavelengths, which was attributed to electron overflow into the p-side of the diode, was maximized, leading to deep-UV LEDs with superior spectral purity. Deep-UV AlGaN heterostructures were processed into single LED chips whose design was optimized to obtain uniform current spreading and low contact resistivity in high-aluminum content n-AlGaN layers. Deep-UV LED chips were flip-chip mounted onto AlN submounts and TO headers using hard soldering and wire bonding, as shown in Fig. 1(a). The performance characteristics of these LEDs were studied with many respects. For instance, the chip design was found to be critical regarding the spatial uniformity of the emitted optical power, as shown in Fig. 1(b). Optimized UV LED devices with a maximum spectral power density at the target wavelength of 226 nm had a peak wavelength at 232 nm and emitted about 4 µW total power with only little parasitic emission around 320 nm (Fig. 2).

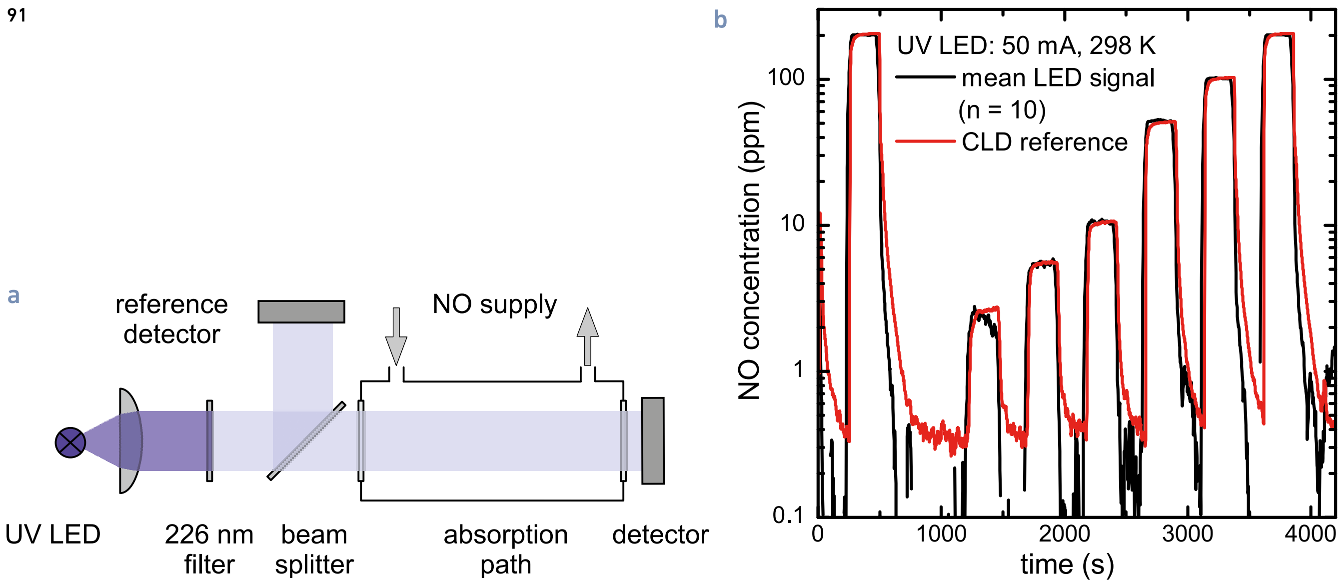

Fig. 3. (a) Schematic of the gas detection system, (b) nitrogen oxide concentration within the absorption path as detected by the LED (black) and the chemical detector reference (red).

These deep-UV LEDs were integrated into a newly developed gas monitoring system. As presented in Fig. 3(a), the UV LED light in this setup is first collimated and then passed through a bandpass filter with a center wavelength of 226 nm and a bandwidth of 2 nm. Subsequently, it is divided into a 500 mm long measurement path and a reference path. NO concentrations between 0 ppm and 200 ppm were injected into the detection cell using nitrogen as carrier gas. Special attention was devoted to thermally stabilize the components for maximum sensitivity. NO concentrations as low as 2 ppm could be resolved, as shown in Fig. 3(b). Moreover, the data was in good agreement with a reference measurement using a chemiluminescence detector. The excellent performance of this first-generation NO gas sensing system using deep-UV LEDs suggests that such systems may outperform and replace conventional detectors in the very near future.

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Die Absorptionslinie von Stickoxid (NO) bei 226 nm eignet sich zur selektiven Detektion dieses Gases mittels UV-LEDs mit entsprechend kurzer Emissionswellenlänge. Solche Bauelemente erfordern jedoch AlGaN-Heterostrukturen mit einem Aluminiumgehalt > 80 %, die technologisch anspruchsvoll sind. In einer Kooperation zwischen dem Ferdinand-Braun-Institut, der Technischen Universität Berlin und der Universität Rostock wurden nun UV-LEDs mit extrem kleiner Emissionswellenlänge von 232 nm entwickelt und erfolgreich zur Detektion von NO eingesetzt. Nach der Optimierung des Schichtstrukturdesigns, der epitaktischen Wachstumsbedingungen, des Chiplayouts sowie der Chipprozesstechnologie konnten spektral reine LEDs mit optischen Leistungen von 4 µW realisiert werden. Zusammen mit einem schmalbandigen Bandpassfilter wurden diese LEDs in ein Gasdetektionssystem implementiert. Damit ließ sich die absolute Konzentration von NO in Stickstoff mit einer Empfindlichkeit von 2 ppm messen. Entsprechende Systeme mit UV-LEDs könnten daher schon bald konventionelle Gasdetektionsverfahren in einigen Bereichen ablösen.

For further information:

https://www.fbh-berlin.com/research/photonics

III-V Electronics

III/V-Elektronik

III/V-Elektronik

Das übergreifende Ziel der Forschungsarbeiten des FBH im Bereich III/V-Elektronik ist, die Grenzen der elektronischen Bauteile hinsichtlich effizienter Leistungserzeugung bei hohen Frequenzen, hohen Spannungen und kurzen Schaltzeiten systematisch zu erweitern.
Das Spektrum reicht von schneller Leistungselektronik über die Mobilfunkfrequenzen im unteren GHz-Bereich bis hin zu Sub-Millimeterwellen. Alle Aktivitäten basieren auf der III/V-Halbleitertechnologie. Sie umfassen derzeit die folgenden Themen:

- ***HF-Leistungsmodule auf Basis von GaN für den Einsatz in Mobilfunk-Basisstationen*** – der Schwerpunkt liegt auf Konzepten zur Reduzierung der Verlustleistung (Supply Modulation) und zur Erhöhung der Frequenzagilität (BST-Varaktoren).

- ***Digitale Leistungsverstärker*** – das FBH entwickelt neue digitale Verstärkerarchitekturen für die drahtlose Infrastruktur, die Flexibilität mit Leistungseffizienz verbinden. Langfristiges Ziel ist der komplett digitale Transmitter.

- ***Terahertz-Komponenten & -Systeme*** – der Schwerpunkt liegt auf integrierten Schaltungen mit Indium-Phosphid (InP) Heterobipolartransistoren (HBTs), derzeit bis zum 250 GHz-Band. Dabei kommt ein Transfer-Substrat-Prozess zur Anwendung, der auch eine InP-auf-BiCMOS-Heterointegration auf Waferebene beinhaltet. Damit können kompakte integrierte Frontend-Module für Radar-, Sensor- und Kommunikationssysteme realisiert werden.

- ***Erkundung von plasmonischen Effekten für die Terahertz-Detektion*** – diese Phänomene versprechen eine Einsatzmöglichkeit von Transistorstrukturen weit oberhalb der klassischen Grenzfrequenzen im 1 THz-Bereich. Wir nutzen dazu die GaN-Technologie.

- ***GaN-basierte Schalttransistoren & Schottkydioden für hohe Spannungen*** – für hocheffiziente Leistungs-Umrichter mit hoher Taktrate, geringem Gewicht und Volumen. Damit eignen sie sich für vielfältige Anwendungen, u.a. im Bereich Elektromobilität.

- ***Transistoren auf Basis neuer Materialien mit großer Bandlücke wie AlN*** – für Anwendungen von der Leistungselektronik bis zum Mikrowellenbereich.

- ***Mikroplasmen & Lasertreiber*** – GaN-Transistoren werden auch dazu genutzt, um kompakte Mikroplasmaquellen, z.B. für die Aktivierung von Oberflächen, zu entwickeln sowie schnelle Hoch-Strom-Treiber, die mit Laserdioden aus dem FBH zu Pulsquellen integriert werden.

Neben der III/V-Halbleitertechnologie erfordern diese Forschungsarbeiten die entsprechende Expertise bei Simulation, Modellierung, Schaltungsdesign und Charakterisierung.

III-V Electronics

The overall target of FBH's research activities in the field of III-V electronics is to push the limits of electronic devices in terms of efficient power generation at high frequencies, high voltages, and short switching times. The frequency spectrum ranges from fast power electronics through the mobile communication bands in the lower GHz range to sub-millimeter waves. All activities are based on III-V semiconductor technology; they presently encompass the following major topics:

- ***Microwave power amplifiers based on GaN for the use in mobile base stations*** – the focus is on concepts reducing power losses (supply modulation) and enhancing frequency agility (BST varactors).

- ***Digital power amplifiers*** – the FBH develops novel digital amplifier architectures for the wireless infrastructure. Long-term target is the complete digital transmitter.

- ***Terahertz components & systems*** – the focus is on integrated circuits up to the 250 GHz band so far, using indium phosphide (InP) bipolar transistors (HBTs). A transferred-substrate process is applied including a wafer-scale InP-on-BiCMOS heterointegration option. With these circuits, compact integrated frontend modules for radar, sensor and communication systems can be realized.

- ***Exploring plasmonic effects for THz detection*** – these phenomena promise device operation well beyond the classical frequency limits and thus open up possibilities for electronic components in the 1 THz range. We use GaN as semiconductor for these developments.

- ***GaN-based switching transistors & Schottky diodes for high voltages*** – for high-efficiency power converters with high clock speed, low weight, and volume. They are well-suited for a great variety of applications, e.g., in the field of electro mobility.

- ***Investigating transistors with new wide-bandgap materials*** – such as AlN for power electronics as well as microwave frequencies.

- ***Microplasmas & laser drivers*** – GaN transistors are also used to develop compact microplasma sources for, e.g., activation of surfaces and high-speed high-current drivers for laser diodes that are integrated into FBH pulse laser sources.

Besides the III-V semiconductor technologies, these research activities require the corresponding advanced simulation, modelling, circuit design, and measurement expertise.

Novel digital microwave PA with improved overall efficiency over a wide power back-off range

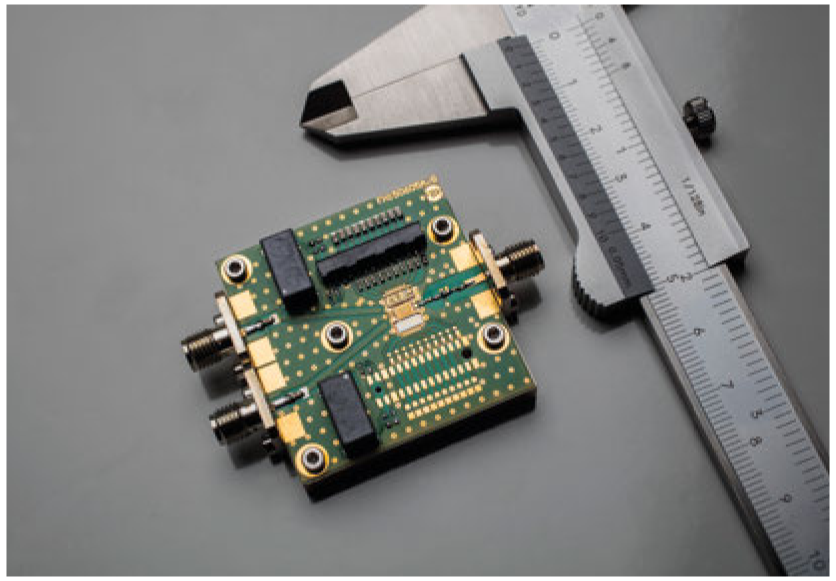


Fig. 1. Realized DPA module for the 800 MHz band including GaN digital amplifier MMIC, band-pass filter, constant-current source, and biasing circuitry; overall module size: 35 x 53 mm².

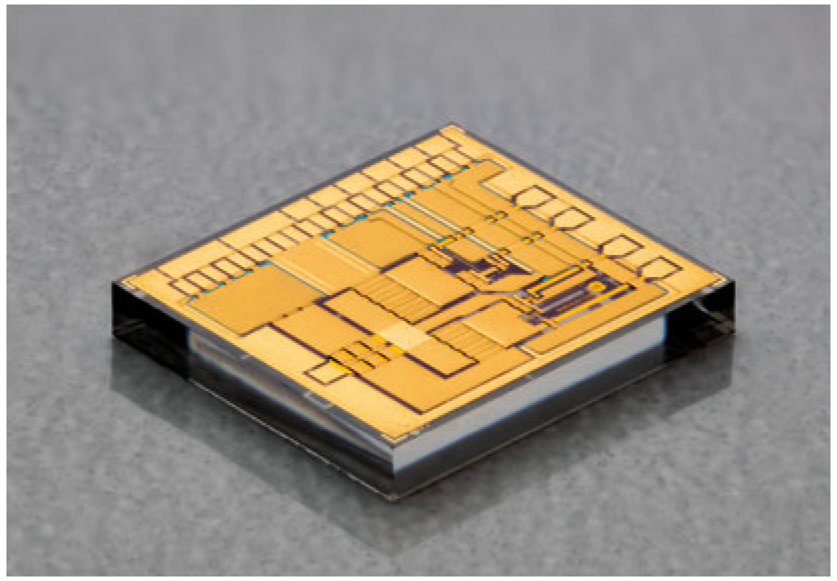


Fig. 2. Fabricated novel digital PA MMIC; chip size: 2.5 x 2.2 mm².

Next-generation wireless communication infrastructure demands for high flexibility, low cost, and high efficiency. This goes along with the growing needs towards wideband, multi-band, and multi-standard features. As a consequence, increasing research efforts have been devoted to non-analog PA realizations in the last years on the way to a fully digital transmitter. One of the most crucial problems is, up to now, the low overall power-added efficiency (PAE) of digital microwave PAs (DPAs) versus power back-off (PBO). The values achieved so far are not competitive to analog concepts like Doherty or envelope tracking.

In 2016, for the first time a GaN-based DPA module reaching high PAE over a wide range of PBO has been realized in the Digital PA Lab at FBH. This is achieved by applying novel circuit approaches and principles known from low-frequency switching converters. The proposed DPA is optimized for the 800 MHz-band, but can, due to its broadband design, be used for other frequencies as well. One only has to change the output filter.

The compact digital amplifier module with an overall size of 35 x 53 mm² includes a GaN power amplifier MMIC (area: 2.5 x 2.2 mm²) and a hybrid input as well as output circuitry for biasing and filtering. The amplifier chip was fabricated using the FBH in-house 0.25 µm GaN HEMT process. The MMIC layout follows a compact digital approach neglecting any redundant 50 Ω connecting structures between the PA parts to improve compactness.

The proposed structure applies for the first time the zero-voltage switching (ZVS) approach in a microwave digital voltage-mode design for increased efficiency of the final-stage. Using ZVS changes the output voltage waveform from rectangular to trapezoidal, which reduces the higher harmonic content in the load. Thus, the filter requirements become more relaxed, but with a slightly decreased maximum output power. Additional advantages of ZVS are the lower speed requirements for the driver due to slower slopes of the output voltage and current leading to a higher efficiency. Moreover, a novel driver circuit was introduced resulting in a very low power consumption, which has been the biggest bottleneck in digital microwave PAs so far.

Applying a single-tone pulse-width modulated (PWM) input signal with varying duty-cycle to emulate power back-off operation the novel amplifier achieves a PAE of 48 % and 40 % at 6 dB and 10 dB PBO, respectively. These PAE values are the best ever reported for microwave digital PAs in the Watt range. A maximum output power of 4.7 W is reached for a drain supply voltage at the final-stage of 30 V and PAE peaks at 62 %. To the best of our knowledge this is the first digital PA module exhibiting PAE values beyond 40 % and a drop of only 19 % points over a 10 dB PBO range. The proposed novel digital power amplifier concept is competitive to the common analog concepts, but offers advantages in terms of flexibility and compactness. Further increasing the final-stage drain supply voltage above 50 V and providing steeper slopes in the input signal (< 100 ps) will improve the results even more in the near future. Moreover, the results will be confirmed with modulated broadband signals like WCDMA and LTE.

The work has been done within the project *Digitale Leistungsverstärker für die drahtlose Infrastruktur der Zukunft* funded by the Leibniz Association.

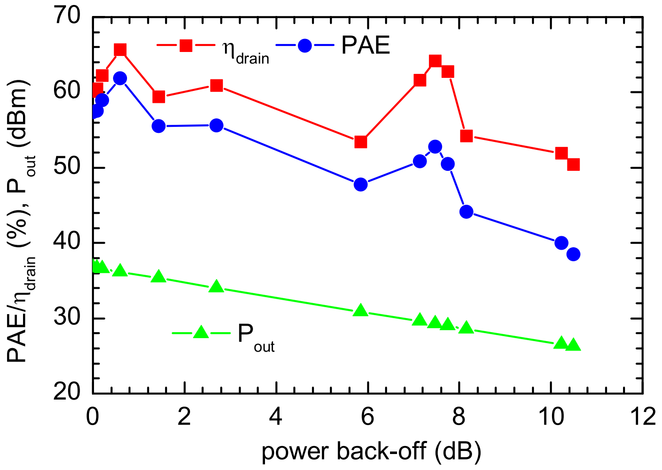


Fig. 3. Measured output power (P_{out}), overall power-added efficiency (PAE) and final-stage drain-efficiency (η_{drain}) vs. power back-off for f_S = 800 MHz and PWM input signal; final-stage drain supply voltage: 30 V.

Die zukünftige drahtlose Kommunikation erfordert eine Systemarchitektur, die besonders effizient, flexibel und kostengünstig ist. Ein vielversprechender Ansatz ist der komplett digital ausgeführte Transmitter inklusive eines digitalen Hochfrequenz-Leistungsverstärkers (DPA). Bisher realisierte DPAs waren jedoch nicht konkurrenzfähig mit vergleichbaren analogen Konzepten wie Doherty oder Envelope-Tracking. Nun hat das FBH in seinem Digital PA Lab 2016 einen neuartigen GaN-basierten DPA für 800 MHz entwickelt, der eine sehr hohe Gesamteffizienz (PAE) bis zu 10 dB unterhalb der Vollaussteuerung erreicht. Das Design verbindet eine neue Schaltungstechnik mit Ansätzen aus niederfrequenten Schaltumrichtern. Das kompakte, nur 35 x 53 mm² große Verstärkermodul beinhaltet die Ein- und Ausgangsbeschaltung mit Spannungsversorgung und Filterung sowie den digital designten GaN-Verstärkerchip, der mit dem FBH-eigenen Prozess realisiert wurde. Der Verstärker erreicht eine maximale Ausgangsleistung von 4,7 W mit einer PAE von 62 %. Darüber hinaus zeigt der DPA bei Betrieb von 6 dB bzw. 10 dB unterhalb der Vollaussteuerung Gesamteffizienzen von 48 % und 40 %. Damit ist das digitale FBH-Verstärkermodul das weltweit erste mit einem derartig geringen Effizienzabfall über eine Variation der Signaleingangsleistung von 10 dB. In dieser Hinsicht konnte erstmals die Konkurrenzfähigkeit des digitalen Ansatzes belegt werden. Darüber hinaus bietet das Konzept viele weitere Vorteile gegenüber analogen Verstärkern hinsichtlich Flexibilität und Kompaktheit.

Publication

T. Hoffmann, A. Wentzel, F. Hühn, W. Heinrich, "Novel Digital Microwave PA with More Than 40% PAE Over 10 dB Power Back-Off Range", IEEE MTT-S International Microwave Symposium Digest 2017, THIF2-12, Honolulu, USA (2017).

GaN HEMT modeling including trapping effects

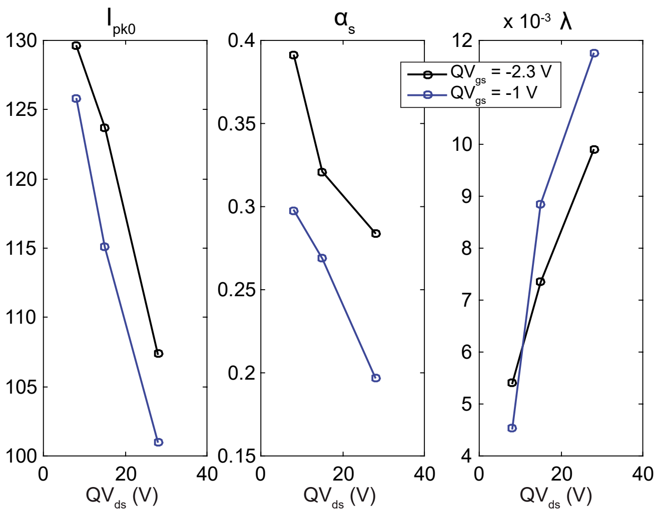


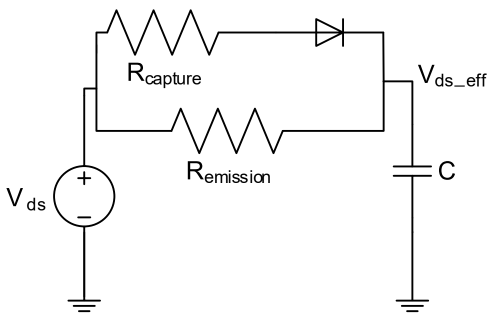
Fig. 1. Dependence of Chalmers model parameter on quiescent drain-source bias voltage.

GaN HEMTs are widely used these days thanks to their excellent microwave performance with regard to high power and low noise. However, modeling their trapping effects still remains a key issue. Since these effects hamper the achievable output power and linearity, much effort has been devoted to measure, understand and describe them in the last years. However, recent dedicated trap models are still not standard in commercial circuit simulators. In 2016, FBH and Brandenburg University of Technology Cottbus-Senftenberg (BTU-CS) have pooled their forces within the Joint Lab BTU-CS – FBH Microwave, also addressing this issue. Our approach allows us to derive an optimized set of parameters which are sensitive to trap states, enabling reasonable large-signal simulation accuracy for standard models by reproducing the trap states from the bias condition.

We employed the Chalmers (Angelov) model as a basis, since it is a frequently used and well-known GaN HEMT model. The model parameter extraction routine is based on pulsed S-parameter measurements for different pulse quiescent drain voltages QV_{ds} = 8, 15, and 28 V, which determine three different trap states. The values of extrinsic elements were extracted from cold-FET measurements. The parameters of the Chalmers model's I_{ds} description were identified by fitting the IV curves to the measured pulsed IV characteristics. It has been found that only three parameters have to be adjusted if the quiescent drain voltage varies: I_{pk0}, α_s, and λ. The other parameters can be kept unchanged without significantly loosing accuracy. Moreover, Fig. 1 reveals that these parameters show a rather linear dependence on the pulse quiescent bias point. Scaling them with bias point prior to simulation allows us to obtain optimum simulation accuracy with a standard Angelov model.

In order to describe the emission and capture process dynamically, we employ a subcircuit shown in Fig. 2. Fig. 3 shows the behavior of the input voltage v_{ds} and the output voltage $v_{ds,eff}$ of this drain-lag subcircuit, together with the simulated output current i_{ds}. When v_{ds} is pulsed from a higher voltage to a lower one, the instantaneous i_{ds} value first does not change and preserves the trap state related to the previous value of v_{ds}. After a long time interval determined by the detrapping process $\tau_{emission} = R_{emission} \cdot C$, i_{ds} gradually reaches a value depending on the trap state of the new value of v_{ds}. On the other hand, when v_{ds} is pulsed to a higher value, the response is much faster, which can be explained by a shorter time constant of the respective trapping process $\tau_{capture} = R_{capture} \cdot C$, with $R_{capture} << R_{emission}$. With this in mind, the output voltage $v_{ds,eff}$ of the subcircuit offers a nice solution to describe the changes in the trap states, which allows to determine the actual values of the three parameters I_{pk0}, α_s, and λ.

Fig. 2. Equivalent circuit used to model trapping effects dynamically.



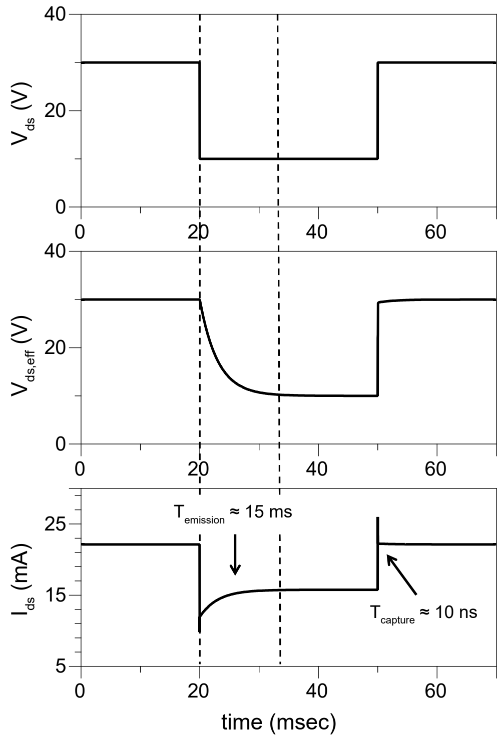


Fig 3. Time waveforms of drain-souce voltage applied to the HEMT (V_{ds}), corresponding trap states determined by the drain-lag subcircuit (V_{ds_eff}), and simulated drain-source current (I_{ds})

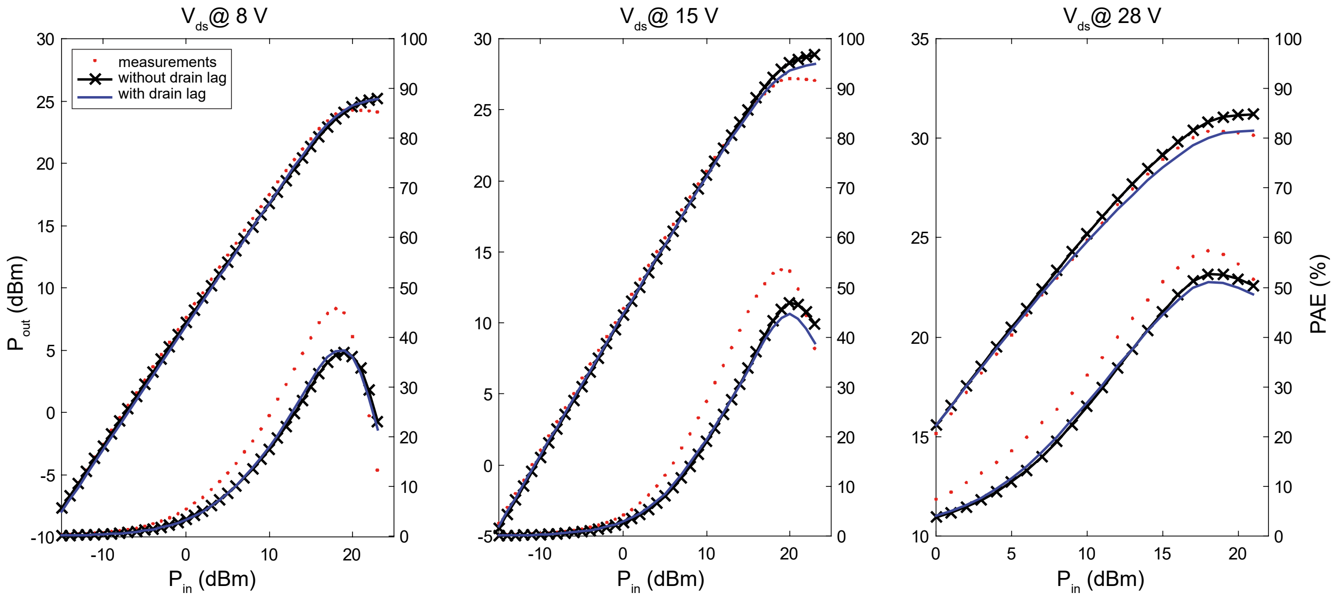


Fig 4. 10 GHz load-pull results of a 4 x 125 µm GaN HEMT. Measurement (symbols) compared to simulation with new drain-lag model (blue) and without new drain-lag model (black).

In order to model the drain-lag effects, we developed a Verilog-A design kit based on this augmented Chalmers model. Fig. 4 presents the comparison between measured and simulated (with and without drain-lag modeling) output power and PAE, for a load condition providing maximum output power, for several V_{ds} voltages. Measurements (symbols) are compared with simulation data of the full model including the above trap description (blue lines) and with the original Chalmers model (black lines with crosses). The latter model misses the subcircuit describing the trap states dynamically, thus the model parameters were adjusted to the bias point. It is seen that the full model provides good prediction of the load-pull behavior. The standard model predicts the linear behavior well, but tends to over-estimate the output power, especially in the saturation region and at higher V_{ds} condition, where the impact of drain-lag effects is more pronounced.

Our approach yields good simulation accuracy relying on an improved Angelov model that determines the trap states dynamically during circuit simulation. But it also allows us to derive an optimized parameter set for a given bias point, estimating the average trap states. This way, our approach enables circuit design with optimum accuracy in different design environments.

Publications

P. Luo, O. Bengtsson, M. Rudolph, "A Drain Lag Model for GaN HEMT based on Chalmers Model and Pulsed S-Parameter Measurements", IEEE MTT-S International Microwave Symposium Digest 2017, Honolulu, USA (2017).

P. Luo, O. Bengtsson, M. Rudolph, "Reliable GaN HEMT Modeling Based on Chalmers Model and Pulsed S-Parameter Measurements", 10th German Microwave Conference (GeMiC) Bochum, DE, ISBN 978-3-9812668-7-0, pp. 441-444 (2016).

P. Luo, O. Bengtsson, M. Rudolph, "Novel Approach to Trapping Effect Modeling Based on Chalmers Model and Pulsed S-Parameter Measurements", Proc. 11th European Microwave Integrated Circuits Conf. (EuMIC), London, UK, pp. 157-160 (2016).

Transistormodelle spielen bei der genauen Beschreibung des elektrischen oder thermischen Verhaltens von Transistoren eine wichtige Rolle. Trappingeffekte sind dabei besonders relevant, da sie Ausgangsleistung und Linearität beeinträchtigen. In jüngerer Zeit wurden entsprechende Modelle vorgestellt, die jedoch in kommerziellen Schaltungssimulatoren bislang nicht genutzt werden. Um diese und weitere Fragestellungen zu bearbeiten, hat das FBH 2016 sein Know-how mit der BTU Cottbus-Senftenberg in dem gemeinsamen Joint Lab BTU-CS - FBH Microwave gebündelt. In diesem Rahmen hat das FBH ein neues Modell für den durch Trapping verursachten Drain-Lag-Effekt entwickelt, das nur drei neue Fitting-Parameter einführt. Damit kann für das Standard-Angelov-Modell ein auf den aktuellen Arbeitspunkt optimierter Parametersatz abgeleitet werden. Das erhöht die Genauigkeit, die sich mit einem erweiterten Angelov-Modell weiter verbessern lässt, indem es die Trap-Zustände dynamisch berechnet. Somit liefert dieser Ansatz die jeweils optimale Genauigkeit in den verschiedenen Schaltungsentwurfs-Umgebungen.

Reconfigurable power amplifiers using barium-strontium-titanate varactors for load modulation

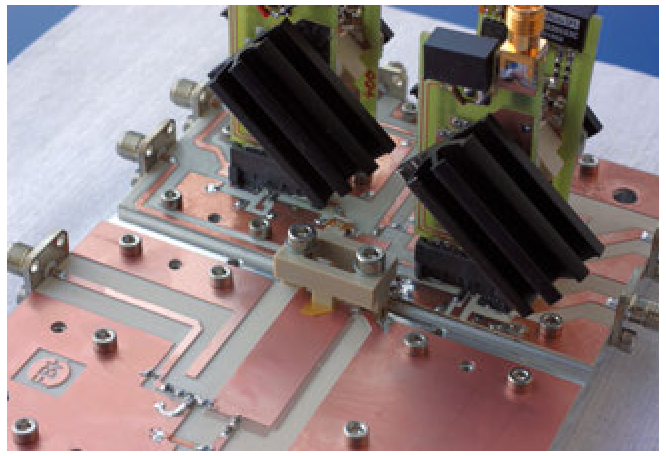


Fig. 1. Power amplifier including modulator switching cards and varactors.

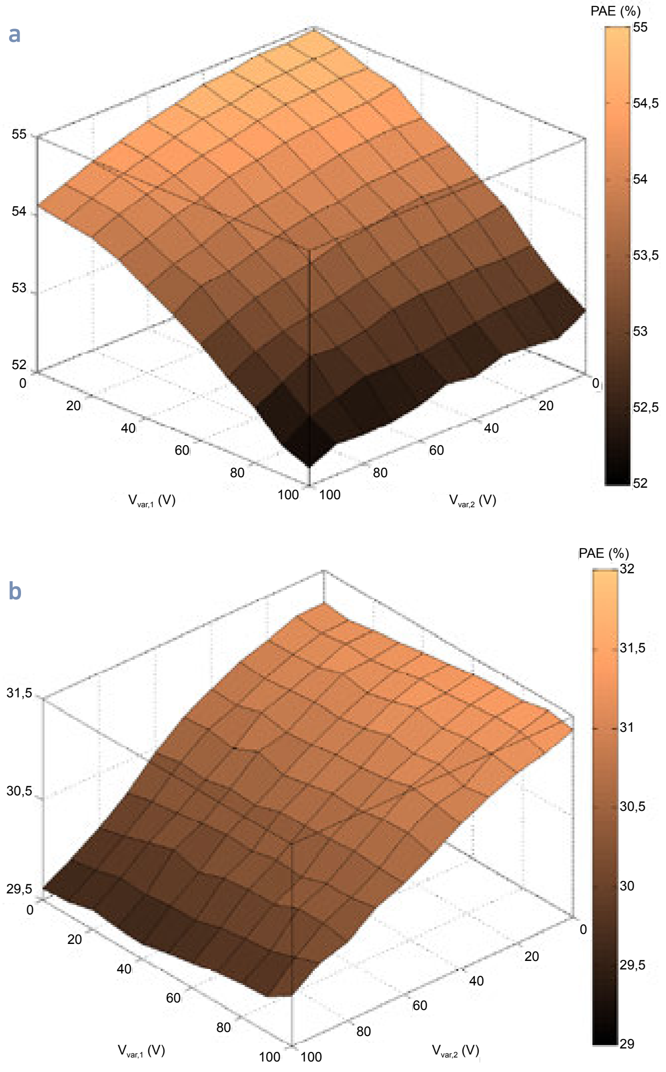


Fig. 2. Measured PAE versus varactor control voltage at saturation power (a) and 6 dB power back-off (b).

Each generation of modern communication systems offers an order of magnitude higher data rates. This improvement is accompanied by a rising complexity of the used modulation schemes, which implies that more amplitude levels and phase conditions have to be encoded. In the case of the transmitter power amplifier (PA) this results in a high peak-to-average power ratio (PAPR). The load impedance optimum for RF power transistors changes with power drive. It is therefore not possible to implement a power amplifier with fixed impedance matching that is equally efficient for all output power levels – at least not if it is operated at constant supply voltage. Load modulation is a technique to prevent the resulting efficiency degradation in power back-off. The matching network of a PA, which transforms the output impedance of the transistor to the impedance of the load, is in load modulated systems equipped with tunable components, usually a varactor. This tunable component can be used to track the optimum load during operation. To maintain signal integrity, the tunable devices used to realize load modulation need to provide high linearity. Barium-strontium-titanate (BST) is a ferroelectric composite which changes its permittivity and therefore its capacitance with an applied electric field. Compared to other tunable devices like semiconductor-based varactor diodes or micro-electromechanical systems, the extremely low static power consumption is an additional benefit. Recent work at the RF Power Lab of the Ferdinand-Braun-Institut, which was pursued in cooperation with Technische Universität Darmstadt and with support of the Karlsruhe Institute of Technology, has shown that thick-film BST fulfills the requirements stated above.

In previous projects, GaN HEMTs manufactured at FBH were integrated in packages together with thick-film BST varactors to demonstrate highly efficient reconfigurable packaged transistor modules. Power levels of 44.4 dBm and 77 % PAE were achieved for modules in the frequency range up to 2.5 GHz with tunability responding within 160 ns. This development became possible by an improved BST composition doped with ZnO-B_2O_3, which lowered the sintering temperature to 850 - 900°C. Thus, fabrication of metal-insulator-metal (MIM) structures became possible, reducing the insertion loss of the varactors to 0.5 dB. Individually packaged varactors showed a power handling capability of 50 W in series configuration and significantly reduced self-heating compared to previous designs.

The tunable transistor modules and the packaged varactors were used to fabricate PAs with load modulation capability, as shown in Fig 1. A supply modulator, which usually drives the drain voltage of a class-G PA, has been utilized for switching the tuning state of the varactors. Its high switching speed, low losses and convenient handling made it also very valuable for varactor control.

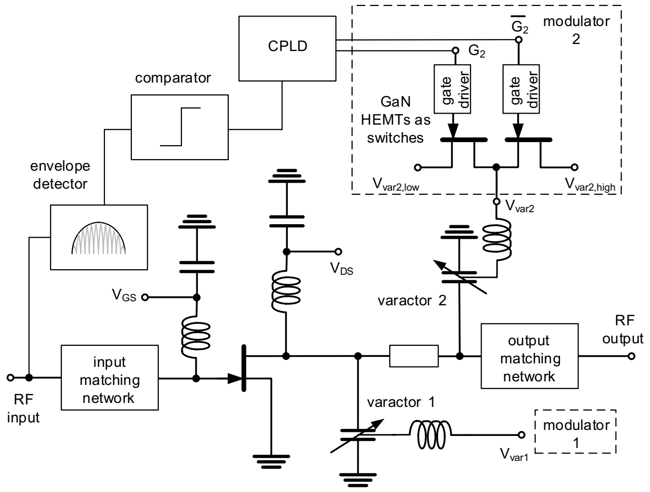


Fig. 3. Schematic drawing of the load-modulated PA test setup.

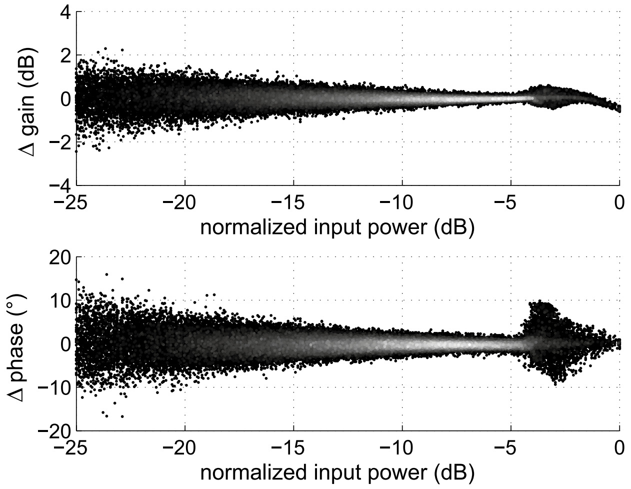


Fig. 4. AM-AM and AM-PM conversion of the modulated PA for an LTE signal with 9 dB PAPR at 1.81 GHz and 35 dBm $P_{out,avg}$.

The PA was designed using a 16 mm gate width GaN HEMT and two packaged thick-film MIM BST varactors. It provides a small signal transducer gain of 16.5 dB, up to 58 % PAE and 45 dBm output power. Fig. 2(a) presents a sweep over the varactor control voltage in power saturation, resulting in variations in PAE. Important for operating a load-modulated PA is to know the load impedances at which PAE peaks for saturation and for the targeted back-off (BO) power level (see Fig. 2(b)) differ from each other. With this knowledge, the output matching can be adjusted to the output power in order to maximize PAE. In this way, modulated measurements with LTE and WCDMA signals were performed using the test setup depicted in Fig. 3. The switching threshold of the MIM BST varactors was adjusted according to the PAPR of the used signal to ensure efficient operation. Fig. 4 illustrates the effect of the varactor switching on the amplitude-amplitude and amplitude-phase conversion for a 5 MHz wide LTE signal. The degradations due to the load switching remain acceptable and the load-modulated PA can be linearized to fulfill the linearity requirements of the LTE standard.

These research activities are funded within the DFG project BE 5397/2-2 *Breitbandige Switch-Mode Hochfrequenz-Leistungsverstärker unter Verwendung von abstimmbaren ferroelektrischen Dickschicht-Komponenten* and the ESA-ITI project 4000111787/14/NL/SC *Tunable pre-matching RF-power GaN-HEMTs for space applications*.

Publications

S. Preis, D. Kienemund, N. Wolff, H. Maune, R. Jakoby, W. Heinrich, O. Bengtsson, "Thick-Film MIM BST Varactors for GaN Power Amplifiers with Discrete Dynamic Load Modulation", IEEE MTT-S Int. Microw. Symp. Dig., Honolulu, USA (2017).

S. Preis, A. Wiens, H. Maune, W. Heinrich, R. Jakoby, O. Bengtsson, "Reconfigurable package integrated 20 W RF power GaN HEMT with discrete thick-film MIM BST varactors", Electronics Letters, vol. 52, no. 4, pp. 296-298 (2016).

J. Ferretti, S. Preis, W. Heinrich, O. Bengtsson, "VSWR protection of power amplifiers using BST components", German Microw. Conf., Bochum, DE, pp. 445-448 (2016).

A. Wiens, S. Preis, C. Schuster, M. Nikfalazar, C. Damm, M. Schuessler, W. Heinrich, O. Bengtsson, R. Jakoby, "Wideband tunable GaN HEMT module utilizing thin-film BST varactors for efficiency optimization", IEEE MTT-S Int. Microw. Symp. Dig., San Francisco, USA, pp. 1-3 (2016).

S. Preis, J. Ferretti, N. Wolff, A. Wiens, R. Jakoby, W. Heinrich, O. Bengtsson, "Response Time of VSWR Protection for GaN HEMT based Power Amplifiers", European Microw. Conf., London, UK, pp. 401-404 (2016).

Die Anforderungen an neue Kommunikationsnetze steigen von einer Generation zur nächsten, vor allem hinsichtlich immer höherer Datenraten. Ein Teil dieses Anstiegs wird durch komplexere Modulationsverfahren realisiert, bei denen mehr Phasen- und Amplitudenstufen eingesetzt werden. Das führt beim Sendeverstärker zu einem steigenden Verhältnis von maximaler zu mittlerer Ausgangsleistung. Mit sinkender Leistung ändert sich die optimale Ausgangsimpedanz von Transistoren; sie verlieren daher bei konstanter Anpassung an Wirkungsgrad. Diesem Effekt lässt sich mittels Lastmodulation entgegen wirken. Barium-Strontium-Titanat (BST) ist eine ferroelektrische Keramik, die als Funktion der angelegten Spannung ihre Permittivität und damit die Kapazität ändert. Diese Kapazitätsänderung erlaubt es, Anpassnetzwerke zu realisieren, die der veränderlichen Impedanz des Transistors folgen können. Das FBH und die TU Darmstadt, unterstützt durch die Materialforschung des KIT, arbeiten seit geraumer Zeit daran und haben verschiedene Verstärker und Module demonstriert, die das Potenzial von BST und GaN mittels Lastmodulation vereinen.

THz plasmonic detectors with high bandwidth and excellent sensitivity

The frequency range between 0.1 - 5 THz offers unique characteristics as many substances, including biological matter and organic materials, are transparent in this region or exhibit unambiguous spectral 'fingerprints'. It is therefore ideally suited for security screening and spectroscopy. Of particular interest are applications using focal plane arrays or THz cameras.

These systems necessitate room-temperature detectors with beyond state-of-the-art performance in sensitivity. Taking advantage of so-called plasmonic effects promises a way to overcome the frequency and sensitivity limits of present semiconductor devices. These phenomena are based on plasma waves, which are manifestations of electron density fluctuations in semiconductor structures, e.g., in the two-dimensional electron gas of a gallium nitride (GaN) high-electron-mobility transistor (HEMT).

Ferdinand-Braun-Institut (FBH) and Goethe Universität Frankfurt (GUF) are developing plasmonic THz detectors based on GaN HEMTs in the frame of the Joint Lab THz Components & Systems. Key aspects are the modelling of the basic plasmonic phenomenon in the GaN HEMT channel and novel structure designs of monolithically integrated structures joining GaN HEMTs with antenna and matching elements.

Realization of the THz detectors is based on FBH's established GaN process line for the fabrication of monolithic microwave integrated circuits (MMICs). The core part of the detector, i.e., the GaN HEMT, has gate lengths varying from 250 nm to 100 nm. It is realized using the appropriate epitaxial structure grown on SiC substrate. The transistor is directly integrated with an antenna structure and matching elements, thus providing boundary conditions for the GaN HEMT channel which yield an efficient plasmonic coupling. Different antenna concepts like bow-tie, log-spiral, tear-drop and slot patch have been verified.

The source and gate contacts are RF-wise short-circuited by forming an MIM structure in order to ensure that the THz radiation received by the antenna couples into the region between drain and gate only. The MIM structure employs SiN_x, which is a typical insulator in MMIC technology. Metallization layers, including NiCr resistors and air-bridge technology, are used to realize the integrated detector. Also, it must be decoupled from neighboring detectors by an appropriate layout. We successfully fabricated single detectors with different types of integrated antennas as depicted in Fig. 1. The detectors exhibit state-of-the-art performance and outstanding bandwidth and sensitivity.

Fig. 2 shows a THz reflection image of a cell phone at 504 GHz taken by a scan with a single detector. The picture was recorded through the back cover of the phone (center photograph). The photograph on the right shows the interior of the phone with the back cover removed. The loudspeaker (bottom left corner), the metal holders for phone and memory card as well as the head phone jack (top right corner, invisible in the optical image) can be identified clearly in the THz image. The overall dynamic range of the recorded reflection image exceeds 40 dB.

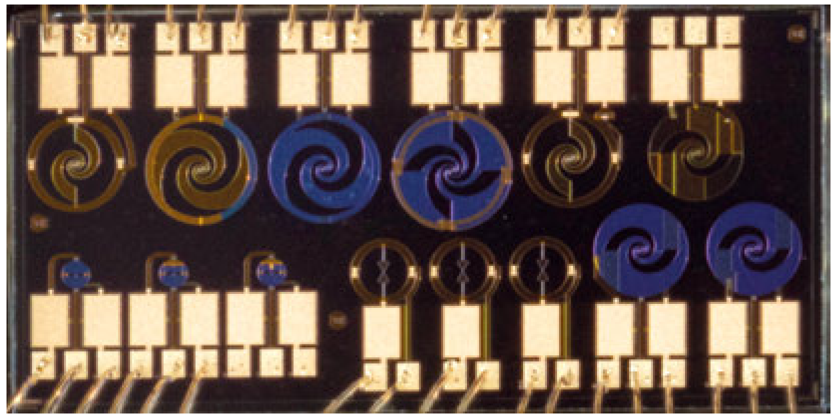


Fig. 1. THz detectors with different antenna concepts and surrounding.

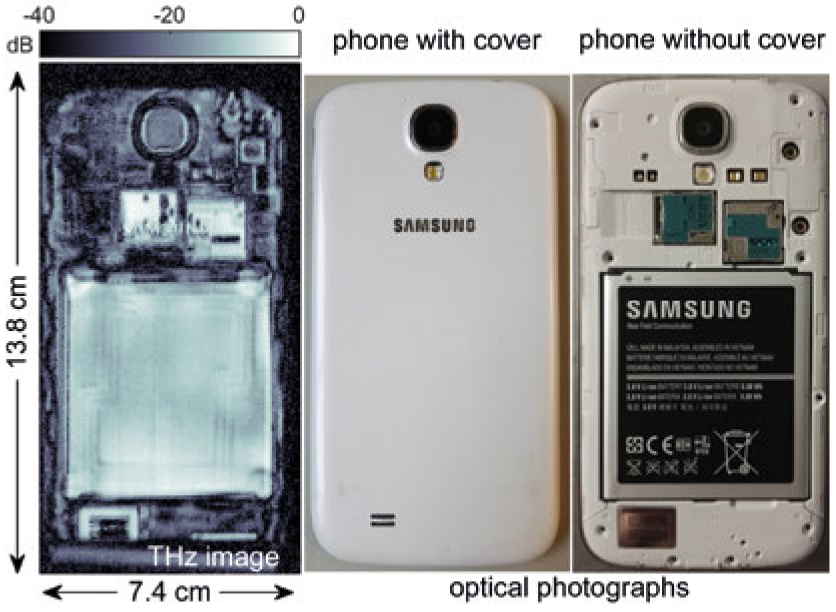


Fig. 2. THz reflection image through cover of a cell phone at 504 GHz.

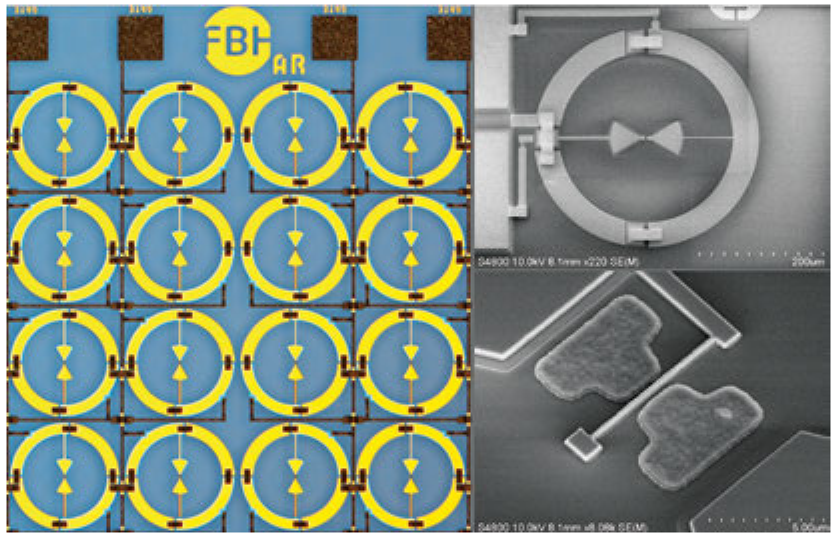


Fig. 3. Optical microscope image of a part of the 12×12 THz detectors array (left), SEM images of a single detector (right up), core part of the detector with GaN HEMT (right bottom).

Such imaging techniques are of interest for industrial applications like quality assurance and process control. Since using a single detector is not feasible for real-time applications due to excessive image acquisition time, FBH has developed and fabricated a 12×12 pixel focal plane array. The array shown in Fig. 3 operates in the frequency range 0.1 - 1.2 THz. We are currently in the process of realizing a complete THz camera based on this array.

Das FBH arbeitet in seinem Joint Lab THz Components & Systems gemeinsam mit der Goethe Universität Frankfurt a. M. an innovativen THz-Detektoren. Mit ihnen soll der THz-Frequenzbereich für industrielle Anwendungen erschlossen werden. Dabei nutzen die Partner gezielt plasmonische Effekte, um breitbandige hochsensitive Detektoren für den Betrieb bei Raumtemperatur zu realisieren. Plasmonen sind Ladungsträger-Dichte-Wellen, die sich entlang eines zweidimensionalen Elektronengases ausbreiten. Das FBH verwendet dafür Galliumnitrid (GaN)-HEMT-Transistoren mit speziell entwickelten Layouts. Diese nutzen monolitisch integrierte Antennenelemente, in deren Fußpunkt der GaN-HEMT platziert ist, und die gleichzeitig die Randbedingungen für eine effiziente plasmonische Ankopplung bieten. Unterschiedliche Detektoren-Layouts sind in Abb. 1 zu sehen. Die meisten industriellen Anwendungen benötigen 2D-Detektorarrays wie in Abb. 3 gezeigt, mit denen Echtzeitbilder erzeugt werden können. Eine THz-Kamera, die auf diesen Detektorarrays basiert, befindet sich zurzeit in der Entwicklung.

Publications

M. Bauer, S. Boppel, J. Zhang, A. Rämer, S. Chevtchenko, A. Lisauskas, W. Heinrich, V. Krozer, H. G. Roskos, "Optimization of the Design of Terahertz Detectors Based on Si CMOS and AlGaN/GaN Field-Effect Transistors", International Journal of High Speed Electronics and Systems, vol. 25, Nos. 3 & 4, 1640013 (2016).

M. Bauer, A. Rämer, S. Boppel, S. Chevtchenko, A. Lisauskas, W. Heinrich, V. Krozer, H. G. Roskos, "High-sensitivity wideband THz detectors based on GaN HEMTs with integrated bow-tie antennas", European Microwave Integrated Circuits Conference (EuMIC), Paris, FR, pp. 1-4 (2015).

Novel gate technology with strain release structure for highly reliable GaN FETs

The embedded gate technology, where the gate is defined by a trench in a pre-existing passivation layer, is quite widespread and commonly used for AlGaN/GaN HEMT fabrication. This gate technology facilitates applying a metal sputter process for Schottky gate fabrication, thus offering technological advantages and leading to higher device stability as well as reliability. As the design of short gates for high-speed devices has to be optimized for minimum parasitic gate cap capacitance the use of tall gates is preferable. This requires high aspect ratio gate trenches.

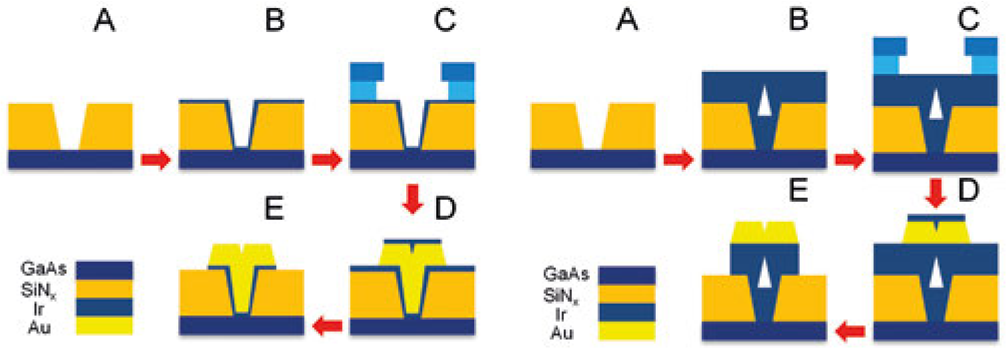


Fig. 1. Gate fabrication process sequence for conventional sputtered gates (left) and newly developed Ir-plug gates with strain relief volume (right).

The presented technology combines high aspect ratio gate trench etching with thick iridium (Ir) film deposition. Ir deposition is optimized such that a coalescence of the Ir film edges occurs at the top of the gate trench. Therefore, an Ir plug is formed with a tiny cavity alongside of the gate in the center. This structure combines conformal coating of the gate trench with a mechanically flexible gate construction (due to the cavity), which largely reduces mechanical strain built up in the gate region. Gate trench technologies, in contrast, completely fill the trench with gold (Au). The new technology thus prevents high mechanical stress and consequently mechanical damage of the structure. Furthermore, the introduction of slanted gate trench sidewalls and sputtered Schottky metal hampers Au diffusion from the highly conductive gate head metallization layer (Fig. 1, left) as this technique ensures conformal metallization in the gate trench. Indeed, Au diffusion from the gate to the semiconductor surface is one of the major degradation mechanisms reported so far. It has been shown that Au diffusing towards the Schottky interface is responsible for increasing the drain and gate leakage current during high temperature operation tests.

Nevertheless, cracks and voids may form either during processing or later during transistor operation. This is due to the roughness of the gate trench sidewalls and owing to mechanical strain generated by thermal expansion mismatch between the gate metal and the passivation layer. In order to completely avoid this difficulty, the “Ir-plug” gate technology shown in Fig. 1, right, has been developed. Using this technology the distance between Au and semiconductor surface is defined by the sum of the Schottky metal thickness and the thickness of the passivation layer. It can be up to 10 times higher as compared to the conventional technology. Another important feature of the “Ir-plug” technology is the strain relief volume formed in the gate body. The tiny hole alongside of the gate accommodates any strain that appears due to mismatch of thermal expansion coefficients of the materials used.

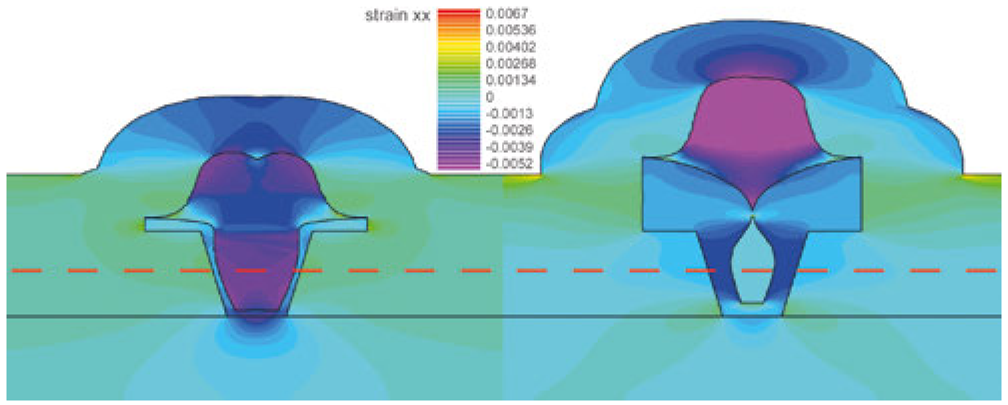


Fig. 2. Strain simulation results obtained for the conventional sputtered gate (left) and Ir-plug gate with strain relief volume (right).

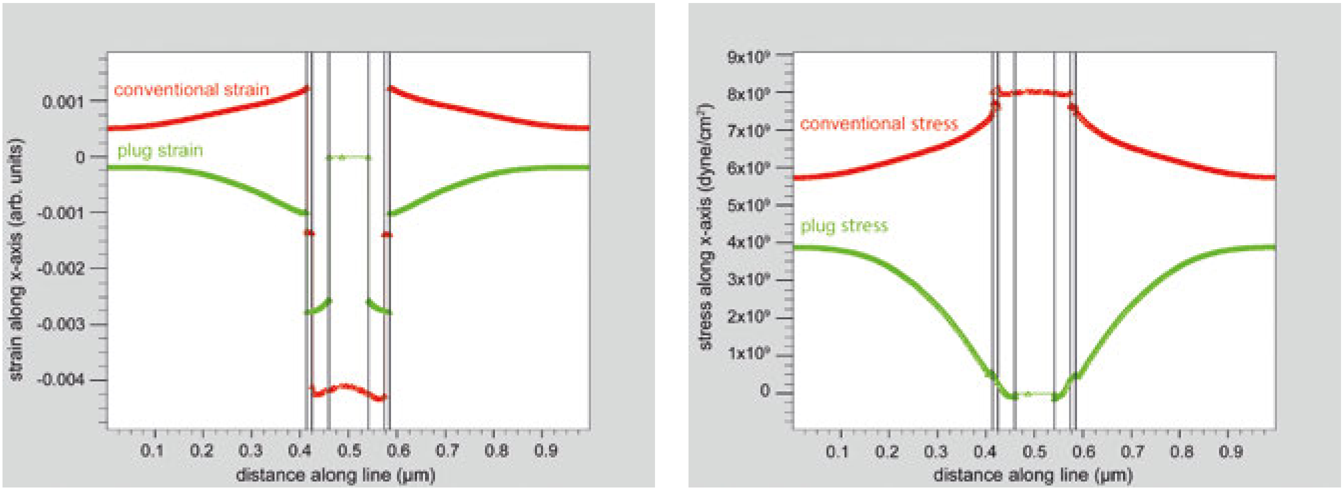


Fig. 3. Strain (left) and stress (right) distribution along the cutline depicted on Fig. 2.

In order to determine stress relief properties of the void inside the gate, Silvaco Victory Stress software was used. The two structures utilized in the simulation are shown in Fig. 2. Conventional Ir-sputter gate (Fig. 2, left) has a 100 nm thick Ir layer and a gate trench filled with Au. Ir-sputter gate with strain relief volume (Fig. 2, right) has a 300 nm thick Ir film that coalesces in the upper part of the trench and does not allow Au penetration inside the trench. The void is therefore formed inside the gate body. In order to simulate the effect of mechanical stress appearing due to the deposition of the second SiN_x film, the whole structure was assumed to be in equilibrium at 350 °C (after deposition of SiN_x film) initially and then cooled down to room temperature. As can be seen from Fig. 2, left, a significant shrinkage of 0.4 % occurs during the cooling process in the conventional structure where the gate body is filled with Au. The consequence of Au and SiN_x shrinkage is the build-up of tensile stress (up to 800 MPa) inside the gate and next to the trench edges (Fig. 3, right, red lines). Fig. 2, right, shows the situation that takes place in the Ir-plug gate, indicating that the void inside the gate body does not shrink during the cooling process. This prevents stress formation: Hence, zero stress inside the gate void and less than 10 MPa stress at the interfaces can be observed (Fig. 3, right, green lines).

Publications

K. Y. Osipov, R. Lossy, P. Kurpas, S. A. Chevtchenko, I. Ostermay, J. Würfl, G. Tränkle, “Iridium Plug Technology for AlGaN/GaN HEMT Short-Gate Fabrication”, Int. Conf. on Compound Semiconductor Manufacturing Technology, Indian Wells, USA, pp. 201-204 (2017).

K. Y. Osipov, S. A. Chevtchenko, R. Lossy, O. Bengtsson, P. Kurpas, N. Kemf, J. Würfl, G. Tränkle, “Developing of K- and Ka-band High Power Amplifier GaN MMIC Fabrication Technology”, Int. Conf. on Compound Semiconductor Manufacturing Technology, Miami, USA, pp. 31-34 (2016).

R. Lossy, H. Blanck, J. Würfl, “Sputtered Iridium Gate Module for GaN HEMT with Stress Engineering and High Reliability”, Int. Conf. on Compound Semiconductor Manufacturing Technology, Denver, USA, pp. 193-196 (2014).

Transistoren, die auf höchste Frequenzen ausgelegt sind, benötigen Gatestrukturen mit kurzer Gatelänge und stark reduzierten parasitären Kapazitäten. Die bestehende „Embedded Gate Technologie“ bei Ka-Band-GaN-MMICs wurde daher mit einer Grabenstruktur in der Passivierungsschicht (Gate-Trench) erweitert. Dadurch lassen sich Gates mit einem hohen Aspektverhältnis herstellen, was die parasitären Kapazitäten drastisch reduziert. Zudem wurden Trench-Ätzprozess und Abscheidung des Ir-Gatemetalls so miteinander kombiniert, dass eine spezielle Struktur realisiert werden konnte. Diese weist innen entlang des Gates einen minimalen, aber gezielt einstellbaren Hohlraum auf. Damit lassen sich die in diesem Gebiet entstehenden mechanischen Verspannungen praktisch komplett abbauen. Verspannungen entstehen im Bauelementbetrieb durch thermische Belastungen und aufgrund der unterschiedlichen thermischen Ausdehnungskoeffizienten der Materialien im Bereich des Gates. Werden mechanische Verspannungen im Gatemetall und an der Passivierungskante gezielt abgebaut, erhöht dies die Zuverlässigkeit des Bauelements. In Experimenten wurde die Eignung dieses Konzepts nachgewiesen und durch Simulationsrechnungen untermauert.

GaN-based vertical n-channel MISFETs for switching applications

Recent progress regarding low-defect density GaN substrates facilitates the development of vertical GaN-based transistors for switching applications. Such vertical transistors represent a desired concept due to their reduced wafer 'foot print'. As compared to lateral HFETs, the area-specific on-state resistance R_{DS_ON} × A is reduced by one order of magnitude down to ~1.0 mΩ·cm². In addition, the possibility of strain-free homoepitaxy allows for growth of thick *n*-GaN drift layers for an off-state blocking capability larger than 1 kV. Therefore, vertical switching transistors facilitate compact assembly with as short as possible inductive loop circuit topologies. As an example, vertical GaN FETs may be hetero-integrated on top of high-power diode lasers as drivers to generate ns-range light output power pulses with reduced self-heating losses. At FBH, we have demonstrated a true vertical *n*-channel MISFET grown by Metalorganic Vapor Phase Epitaxy (MOVPE) on a sapphire substrate.

The development of vertical GaN switching transistors faces three major challenges: First the technological implementation of optimized epitaxial layers for vertical FETs (as presented in "GaN npn structures for vertical FETs" section, p. 118), second the harnessing of gate trench etching and gate insulator technology for channel inversion and gate modulation, and third the process module integration towards a full vertical topology.

Fig. 1 (left) shows the basic epitaxial layers and the GaN vertical MISFET device structure. The epitaxial stack consists of an n^+-doped GaN layer for the bottom drain contact, an n^--doped GaN drift layer to support the blocking strength, followed by a *p*-doped GaN blocking layer and an *n*-doped top layer for the source ohmic contact. The gate electrode is placed on a slanted trench etched into the epitaxial stack. A conformal deposition of aluminum oxide (Al_2O_3) using Plasma Enhanced Atomic Layer Deposition (PEALD) creates an inversion layer at the interface to the *p*-GaN layer and insulates the gate's positive potential from the semiconductor layers. The whole structure has also been implemented in a physics-based device simulator (Silvaco Atlas). Fig. 1 (center) shows the principal transistor conduction operation. As the gate electrode on top of the insulator is positively biased with respect to the source electrode, negative image charges are accumulating at the *p*-type GaN-insulator interface, resulting in carrier inversion. At on-state the inversion channel layer enables electrons flowing from the source to the drift layer and further to the drain electrode. The devices are normally-off, which means that the channel is closed at zero gate bias. In this case, the high drain mainly drops across the n^--GaN drift region.

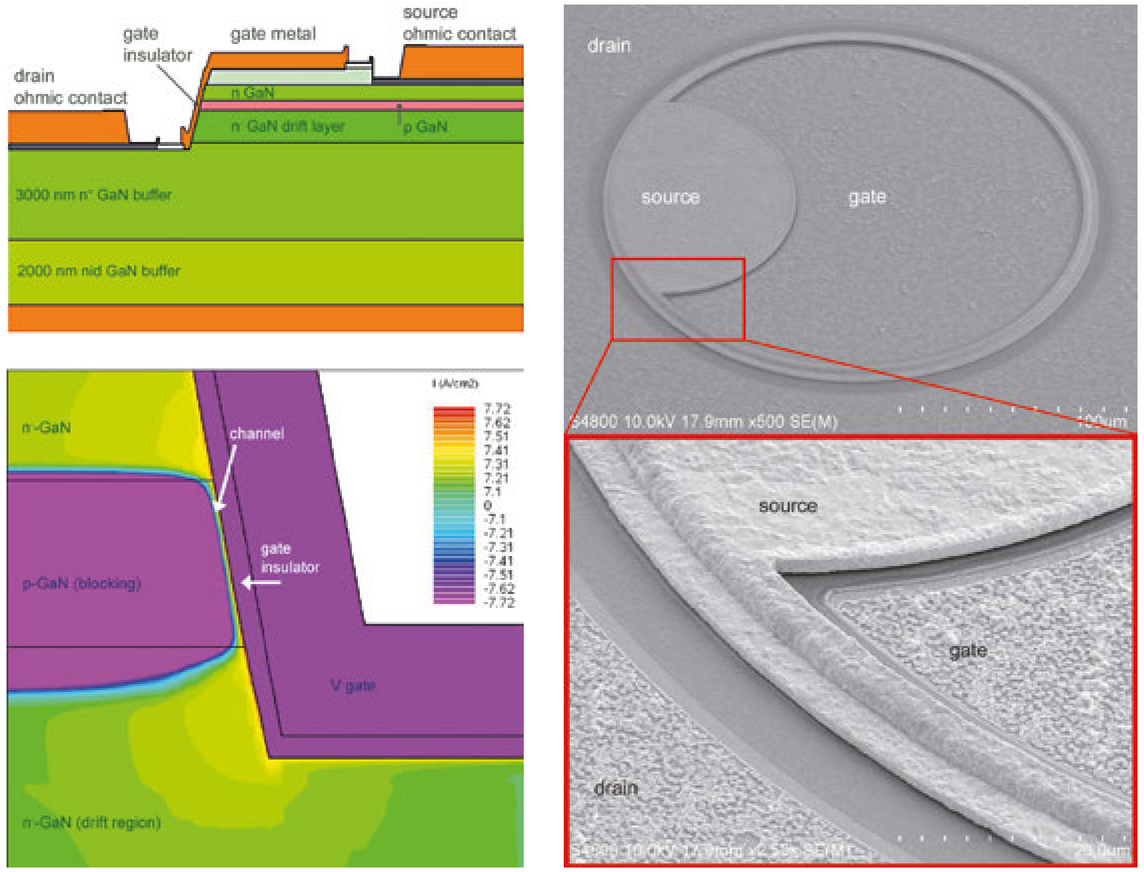


Fig. 1. Cross section of *n*-channel MISFET structure (top left); physics-based simulation of channel current density in on-state conduction operation at V_{ds} = +5 V and V_{gs} = +10 V (bottom left) and SEM micrograph of the manufactured circular GaN MISFETs.

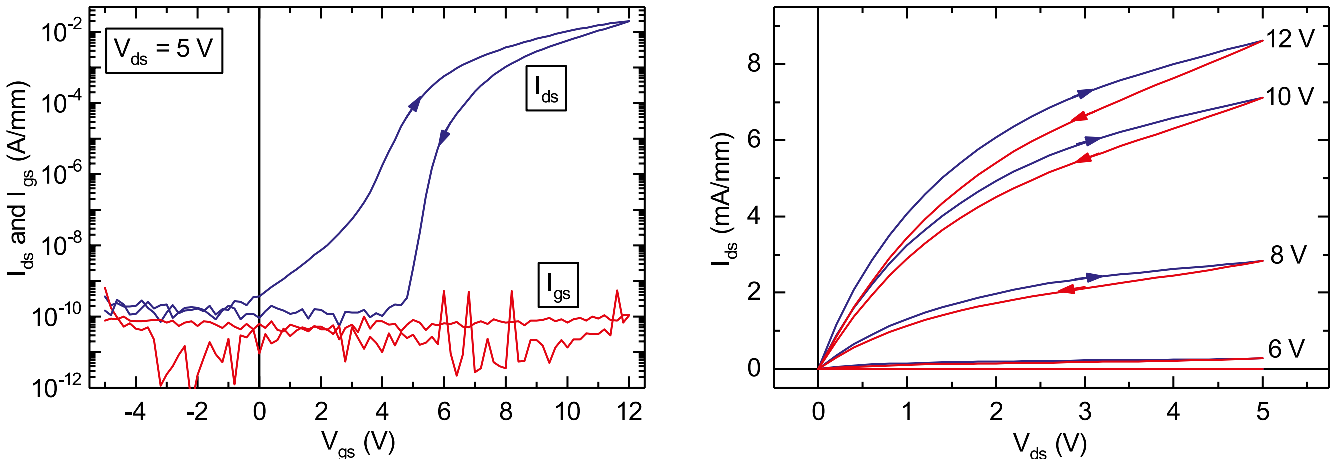


Fig. 2. Vertical GaN MISFET transfer characteristics and gate leakage data measured at V_{ds} = 5 V (left) and I-V output characteristics (right). The measurements have been ramped in forward and reverse direction to highlight hysteresis effects.

As depicted in Fig. 1 (right), circular MISFETs with 200 µm diameter have been manufactured by defining a dry-etched gate trench with 78° inclination down to the drain contact layer. An evaporated metal stack activated by rapid thermal annealing forms source and drain ohmic contacts. The gate insulator consists of a 20 nm thick Al_2O_3 layer formed by PEALD, combined with in situ NH_3 plasma surface pretreatment prior to deposition. As the gate metal electrode has to be placed on the inclined sidewalls of the gate trench, a conformal gold electroplating technology has been developed using TiW/Au as plating base.

Fig. 2 shows the transfer and output characteristics of the vertical GaN MISFET power transistor and demonstrates a maximum drain current of ~20 mA/mm and on-state resistance of ~200 Ohm*mm. Thanks to the highly robust Al_2O_3 gate oxide the gate leakage current remains below the detection limit ~10^{-10} A/mm at a positive gate bias of 12 V. An effective channel inversion has now been demonstrated with on-off ratio of >10^8 at a maximum subthreshold slope of ~200 mV/decade. As can be seen in Fig. 2 the devices are still suffering from hysteresis effects. Together with a further improvement of channel inversion the reduction of hysteresis will be one of the major topics of ongoing activities.

This work has been performed in frame of the German-Polish project *PioneerGaN* under grant no. 10157776, funded by the European Fond for Regional Development (EFRE).

GaN-Transistoren mit vertikal angeordneter Transistortopologie eignen sich hervorragend für die Chip-auf-Chip-Integration mit optoelektronischen Komponenten wie etwa Diodenlasern. Auf diese Weise lassen sich schnell gepulste Lichtquellen realisieren, für die das FBH intrinsisch vertikale GaN-Transistoren entwickelt hat. Deren Funktionsprinzip basiert auf der Ladungsträgerinversion an der Grenzschicht zwischen dem nahezu vertikal angeordneten Gateoxid und dem Halbleiter. Im Rahmen des deutsch-polnischen Projekts *PioneerGaN* ist es erstmals gelungen, derartige auf „Trenchgates" basierende Bauelemente erfolgreich zu realisieren und damit an den weltweiten Stand dieser Technologie anzuschließen. Die Bauelemente zeigen eine selbstsperrende Steuercharakteristik und wurden zunächst auf Saphirsubstraten hergestellt. Die Technologie wird derzeit auf GaN-Substrate transferiert, die eine bessere Defektdichte bieten. Die bereits verfügbaren Daten der Testbauelemente lassen erwarten, dass nach entsprechender geometrischer Skalierung Halbleiter-Diodenlaser hybrid integriert werden können.

Loss optimal drive of high voltage GaN HFETs considering cross conduction

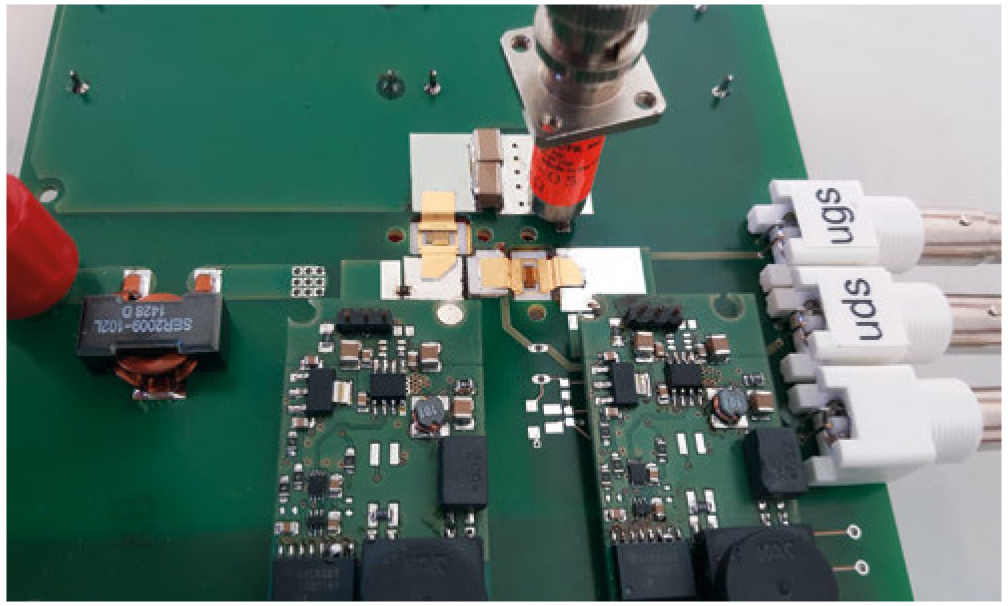


Fig. 1. GaN half bridge test setup with coaxial current shunt and 110 mΩ/600 V transistors.

Current GaN power devices offer the possibility to increase switching speed to an unprecedented level for power electronic applications. High voltage devices with blocking voltages above 600 V achieve voltage slopes higher than 200 V/ns. These fast transients minimize switching losses. However, they lead to 'cross conduction' as a side effect during hard switching processes in half bridge topologies. This effect is known from MOSFETs, but becomes more critical in GaN transistors due to the GaN-specific low C_{DG}/C_{GS} ratios. The internal chip capacitances enable a feedback to the gate source voltage during transients of the drain source voltage (Fig. 2). Consequently, the gate source voltage may rise above the threshold voltage during a high positive dv_{DS}/dt. The transistor turns on unintentionally and a cross current appears, which increases the switching losses. Therefore, a gate driver concept preventing an excessive rise of gate source voltage is necessary, thus minimizing switching losses.

The effect of cross conduction has been investigated with 600 V 110 mΩ FBH GaN HFETs in a half bridge topology (Figs. 1 and 2). The top transistor is not switched actively; its gate is biased with a constant negative gate source voltage. As GaN transistors do not have a body diode, the top transistor itself has to conduct the load current in reverse direction when the bottom transistor turns off. Furthermore, while turning on the bottom transistor, the voltage across the top transistors has to rise rapidly causing a high dv_{DS}/dt. This biases its internal C_{DG}/C_{GS} capacitive voltage divider and may result in a spurious turn-on of the device, which leads to additional temporary cross current.

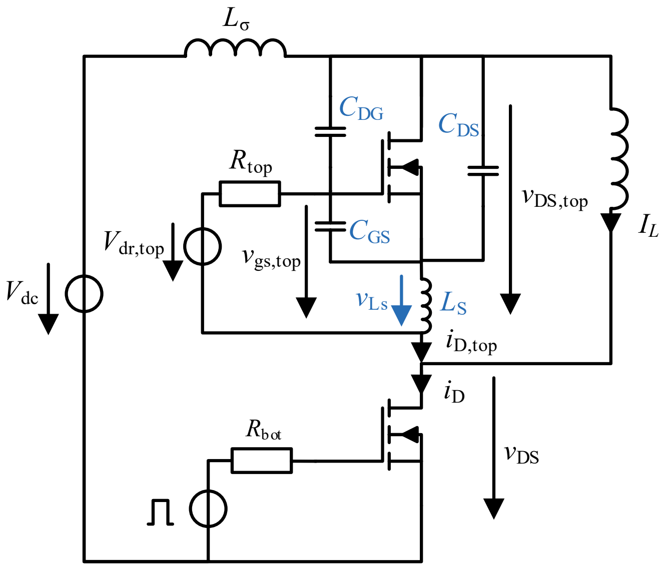


Fig. 2. Equivalent circuit of the test setup.

The measured switching transients in Fig. 3 are taken from the bottom transistor. They reflect the drain voltage and drain current change during a switching event and strongly depend on the gate drive conditions of the top transistor ($V_{dr,top}$). The more the top transistor is biased into pinch-off the steeper the transitions and the less pronounced the current overshoot (Fig. 3b), which is a measure of cross conduction. In principal, a lower gate driver resistance at the top transistor also reduces cross conduction as this diminishes charging of C_{GS} of the internal capacitive voltage divider. This may be a problematic solution as this measure is conflicting with the chip internal gate resistance and the driver IC resistance. Furthermore, a low gate resistance may lead to parasitic oscillations during switching. As seen in Fig. 3, a lower gate driver voltage level reduces cross conduction and hence switching losses without resonance issues. As the top transistor has to take over the full reverse load current during turn-off of the bottom transistor, a lower gate driver voltage during off-state increases reverse conduction losses. Fig. 4 depicts this dependency. As a countermeasure it is obvious that the reverse conduction losses can be strongly reduced by turning on the top transistor (V_{GS} = 5 V) at the right time. Unfortunately, the turn-on in reverse direction cannot be performed directly while turn-off of the bottom transistor. A certain dead time is needed to avoid a short circuit.

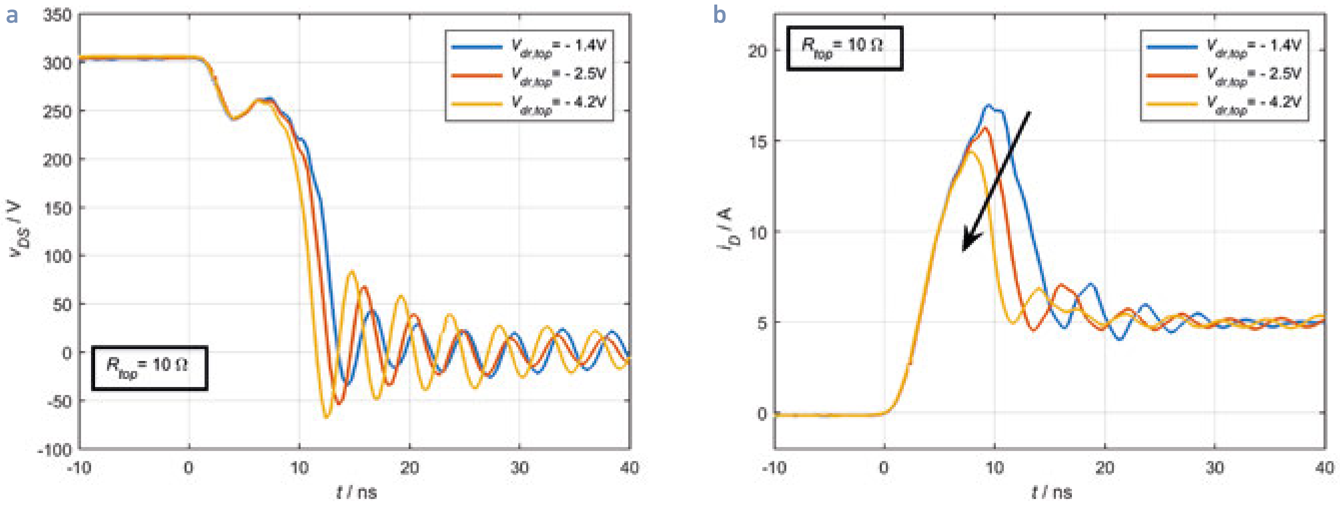


Fig. 3. Drain-source voltage (a) and drain current (b) at the active bottom transistor, R_{npt} = 27 Ω.

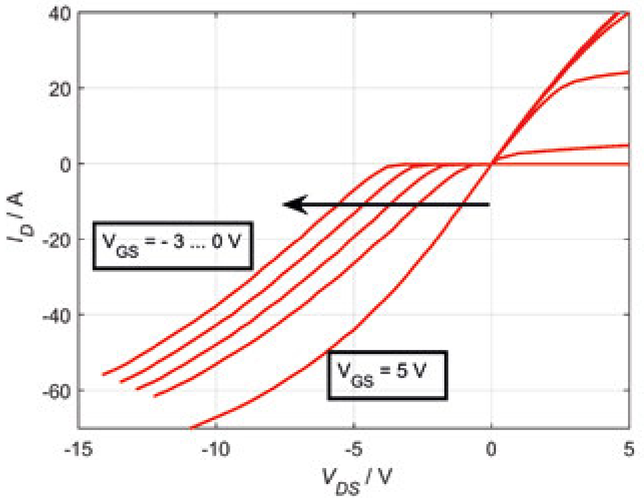


Fig. 4. V-I characteristic of the 110 mΩ/600 V transistor in the 3rd quadrant.

Since a lower driver voltage level of the top transistor reduces switching losses but increases reverse conduction losses, a loss optimum driver voltage exists. Furthermore, it is advisable to turn on the top transistor at a safe positive gate voltage to allow for low-loss conduction of the load current in the top transistor as soon as the bottom transistor is turned off safely (dead time). In order to achieve loss optimum operation, a gate driver with low minimum impedance as well as variable voltage levels and gate resistances for turn-on and turn-off is therefore necessary. Such a driver has been developed in the frame of this work within the Joint Lab Power Electronics, a joint initiative of FBH and TU Berlin.

These activities have been partially funded by the German Research Foundation (DFG) within the project *Adapted switching technology for GaN power electronics* under grant no. WU 172/5-1.

Aktuelle GaN-Leistungshalbleiter ermöglichen sehr schnell schaltende Umrichter mit Spannungssteilheiten > 200 V/ns bei einer Blockierspannung über 600 V. Dies reduziert die Schaltverluste, führt jedoch zu mehr Querleitfähigkeit (cross conduction) in Halb- oder Vollbrückenkonfigurationen. Diese Problematik ist wegen der sehr hohen Spannungssteilheit und des kleinen C_{DG}/C_{GS}-Verhältnisses bei GaN-Transistoren besonders kritisch. Im Rahmen des Joint Labs Power Electronics wurden entsprechende Untersuchungen an 110 mΩ/600 V HFETs des FBH in einer Halbbrückentopologie durchgeführt. Diese GaN-Transistoren weisen im 3. Quadranten eine Diodencharakteristik auf (Fig. 4) und können den Strom bei Bedarf in Rückwärtsrichtung leiten. Die Querleitfähigkeit kann reduziert werden, indem das Spannungslevel des Gatetreibers während der Blockierphase abgesenkt wird. Dadurch vergrößert sich der Abstand zur Schwellenspannung, was jedoch zu höheren Durchlassverlusten während der Rückwärtsleitphase führt. Für einen verlustoptimalen Betrieb wurde daher eine Treiberschaltung entwickelt, die variable Spannungslevels liefert und so die Durchlassverluste minimiert. Im Dauerbetrieb können die Bauteile damit nach einer möglichst geringen Totzeit gezielt in Rückwärtsrichtung eingeschaltet werden.

Publication

J. Böcker, C. Kuring, S. Dieckerhoff, O. Hilt, J. Würfl, "Cross Conduction of GaN HFETs in Half-Bridge Converters", PCIM Europe, Nürnberg, DE (2017).

GaN-on-Si wafer benchmarking for 600 V normally-off GaN switching transistors

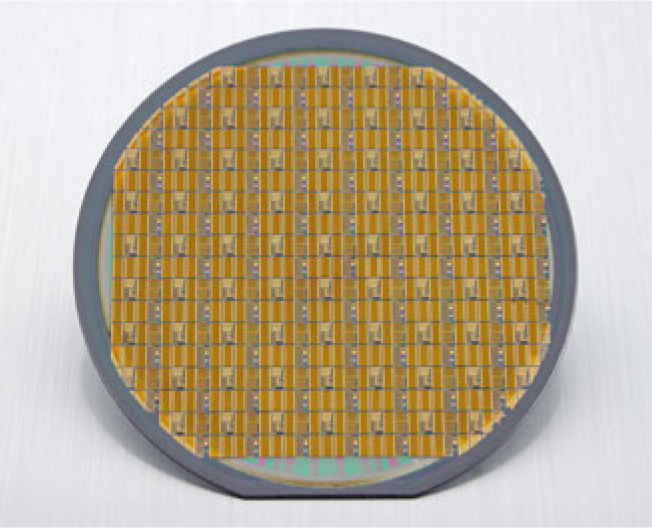


Fig. 1. 4" GaN-on-Si wafer with normally-off 600 V/70 mΩ transistors.

Design and technology of GaN-based high-voltage switching transistors have reached a considerable degree of maturity in recent years. These transistors meanwhile show impressive performance benefits in terms of switching speed, gate charge, output capacitance, and area-specific on-state resistance – and may outperform Si-based transistors like superjunction MOSFETs or IGBTs in these parameters. An essential feature of the lateral GaN device technology is the use of silicon wafers as substrate along with MOVPE-based hetero epitaxy to grow the electrically active GaN-based semiconductor layers on top of them. This allows utilizing large-scale diameter wafers and – at least partially – standard processing equipment which is already in use for silicon technology. Thus, costs of GaN-based devices may come close to those of Si-based devices – an essential advantage over other emerging wide-bandgap transistor technologies for power-electronic applications like SiC or Ga_2O_3.

FBH applies a standardized processing scheme for manufacturing GaN-based 600 V / 70 mΩ normally-off switching transistors for power-electronic applications. Commercial 4" GaN-on-Si wafers (Fig. 1) from different Japanese and European manufacturers have been used and compared in a recent study.

GaN-on-Si epitaxy for 600 V AlGaN/GaN HFETs is a particular challenge. As compared to other substrate materials (i.e. sapphire or SiC), silicon has a larger lattice mismatch and a larger thermal expansion coefficient mismatch with respect to GaN. This makes the strain management for thick GaN layers crucial, and the resulting wafer bowing limits the GaN buffer thickness to approx. 5 - 6 µm. On the other hand, thick GaN buffer layers are needed for high-voltage isolation since silicon substrates are conductive. Incorporation of deep acceptor traps by using carbon doping is a common approach to still achieve the required breakdown strength. However, the introduced trap states may charge up during high-voltage off-state device condition, and the trapped charges degrade the transistor channel conductivity after switching the transistor to on-state. This dispersion phenomenon is known as dynamic on-state resistance (R_{ON}) increase. The doping profile and other growth parameter have thus to be adjusted for a feasible compromise between high vertical blocking strength, high lateral blocking strength, and low dynamic on-state resistance. This trade-off situation has been analyzed more thoroughly by comparing wafers from four different vendors.

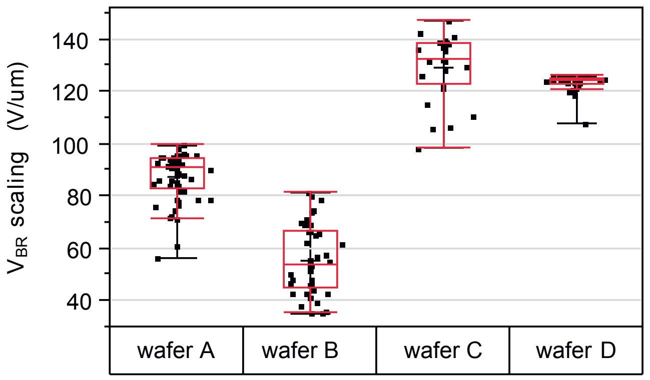


Fig. 2. Breakdown voltage scaling in V per µm gate-drain separation for four different commercial GaN-on-Si wafers.

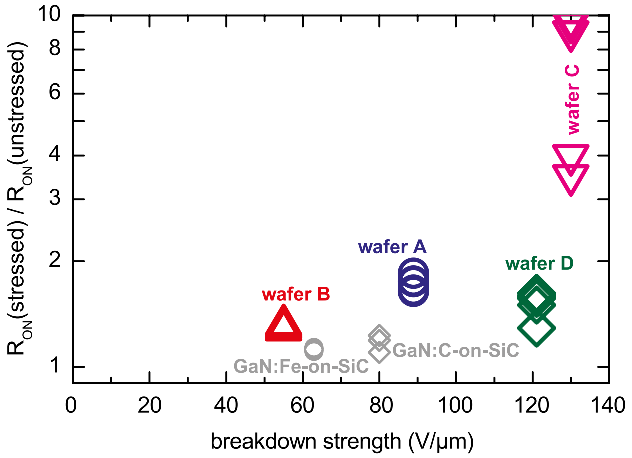


Fig. 3. Dynamic on-state resistance increase versus lateral breakdown strength scaling. R_{ON} was determined 0.2 µs after switching from 65 V off-state drain bias into the on-state. Results for two FBH-grown GaN-on-SiC wafers are shown in gray.

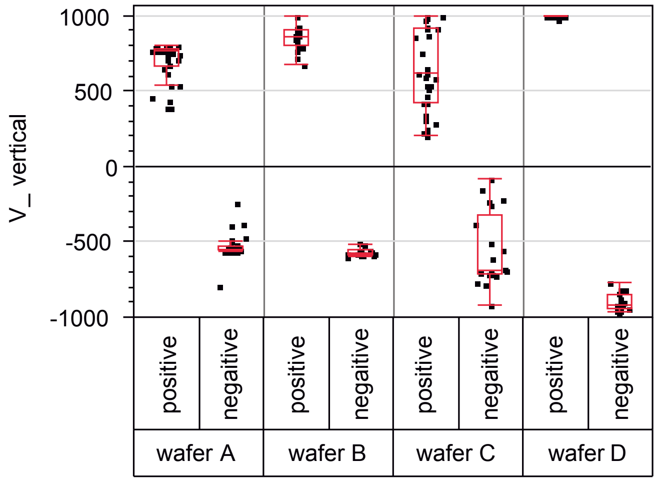


Fig. 4. Vertical blocking voltage of the GaN-based layers for the 4 GaN-on-Si wafers. The bias (maximum 1000 V) was applied to a top ohmic contact with the substrate bottom side grounded.

High lateral transistor breakdown strengths V_{Br} > 50 V/µm can be observed for the different wafers; but V_{Br} deviates by more than a factor of 2 (Fig. 2). Breakdown strength is defined as breakdown voltage per gate-drain distance. The used strong buffer doping for obtaining high breakdown strength compromises the dynamic transistor characteristics (Fig. 3). Wafer C has 130 V/µm breakdown strength, but the dynamic R_{ON} increase (> x3) is not acceptable for efficient switching performance. In contrast, wafer B has the lowest dynamic R_{ON} increase (~ x1.3), but also the lowest breakdown strength (52 V/µm). Wafer D appears to be the feasible compromise offering moderate dispersion and high V_{Br}.

The trade-off situation between V_{Br} and dynamic R_{ON} is apparent when comparing wafer A and wafer B. The active epitaxial structures are very similar, but differ with regard to the on-set of the carbon-doped GaN buffer region that starts at different depths beneath the 2DEG channel: 100 nm for wafer A and 500 nm for wafer B. The thinner non-doped GaN channel of wafer A offers a higher breakdown strength, but trapped charges in the doped buffer are closer to the channel electrons and generate more dispersion.

Reproducibility inside the wafers has been found to be an additional problem, becoming apparent for the distribution of the vertical blocking strength of the wafers (Fig. 4). + 600 V vertical blocking is needed for transistor operation with source-connected substrates. However, many probed structures on wafer A and wafer C do not reach this limit although the median vertical breakdown strengths are above + 600 V. In conclusion, only wafer D can be used for fabrication of reliable 600 V switching transistors.

This work was supported by Federal Ministry for Education and Research (BMBF) LESII project *ZuGaNG* under contract No. 16ES0079.

Durch GaN-Halbleiterschichten, die auf Siliziumwafern gewachsen werden, können die hohen Funktionalitäten von GaN-Leistungstransistoren mit der kostengünstigeren siliziumbasierten Halbleiterproduktion kombiniert werden. Allerdings ist diese GaN-auf-Si-Epitaxie für 600 V Transistoren extrem anspruchsvoll. Die Gitterkonstanten und der Wärmeausdehnungskoeffizient von Silizium lassen sich nur schlecht an GaN anpassen. Das führt zu Waferverbiegungen und begrenzt die GaN-Schichtdicke auf etwa 5 - 6 µm. Das FBH hat daher kommerzielle 4" GaN-auf-Si Wafer aus Japan und Europa untersucht, auf denen selbstsperrende 600 V GaN-Schalttransistoren mit standardisierten Prozessmodulen hergestellt wurden. Dabei wurde auf einigen Wafern die erforderliche vertikale Spannungsfestigkeit von > 600 V nicht erreicht. Die laterale Spannungsfestigkeit variierte um den Faktor 2 - 3, zudem wurden große Unterschiede im dynamischen Einschaltwiderstand festgestellt. Nur einem Waferhersteller gelang es, ausreichende Spannungsfestigkeit mit geringer Dispersion zu kombinieren.

Publications

O. Hilt, E. Bahat-Treidel, A. Knauer, F. Brunner, R. Zhytnytska, J. Würfl, "High-voltage normally OFF GaN power transistors on SiC and Si substrates", MRS Bull., vol. 40, no. 05, pp. 418-424 (2015).

O. Hilt, R. Zhytnytska, J. Böcker, E. Bahat-Treidel, F. Brunner, A. Knauer, S. Dieckerhoff, J. Würfl, "70 mΩ/600 V Normally-off GaN Transistors on SiC and Si Substrates", Proc. 27th International Symposium on Power Semiconductor Devices & IC's, May 10-14, Hong Kong, CN, pp. 237-240 (2015).

For further information:

https://www.fbh-berlin.com/research/iii-v-electronics

III-V Technology

III/V-Technologie

III/V-Technologie

Im Forschungsbereich III/V-Technologie bündelt das FBH sein Know-how und seine Ressourcen in der Material- und Prozesstechnologie sowie in der Aufbau- und Verbindungstechnik. Diese bilden die Basis für die Entwicklung von Bauelementen in den Forschungsbereichen Photonik und III/V-Elektronik:

- ***Epitaxie Nitride*** – Heterostrukturen für UV-LEDs, UV-Fotodetektoren, violette Laserdioden und GaN-Transistoren. Diese Heterostrukturen sind die Basis für die Entwicklung der entsprechenden Bauelemente am FBH. Weiterhin wird an HVPE-Prozessen für GaN- und AlGaN-Substrate und -Templates geforscht.

- ***Epitaxie Arsenide*** – Heterostrukturen für GaAs-Laserdioden sowohl für die Bauelemententwicklung am FBH als auch für externe Kunden. Darüber hinaus werden SAM-Strukturen für gepulste Lasersysteme entwickelt.

- ***Prozesstechnologie*** – Prozesse für eine Vielzahl von GaAs-, InP- und GaN-Bauelementen auf Waferdurchmessern von 2" bis 4". Diese werden auf der industriekompatiblen und zugleich flexiblen Prozesslinie durchgeführt und beständig weiterentwickelt.

- ***InP Devices & SciFab*** – InP-HBTs für THz-Frequenzen, die die Basis für die THz-Systeme am FBH darstellen. Integriert mit Si-BiCMOS-Schaltkreisen wird diese Technologie in Kooperation mit dem Leibniz-Institut IHP auch für externe Kunden bereitgestellt.

- ***Aufbau- und Verbindungstechnik*** – die Bauelemente werden auf Wärmesenken oder in Gehäuse eingebaut und damit für den Aufbau von Modulen und Systemen nutzbar gemacht.

- ***Materialanalytik*** – unterstützt die Entwicklungen in der Epitaxie durch Charakterisierung der Eigenschaften der Halbleiterstrukturen. Diese Kompetenzen werden auch für die Entwicklung von Prozess- und Montageschritten sowie für die Analyse von Ausfallursachen der entwickelten Bauelemente eingesetzt.

Wir nutzen unsere technologische Infrastruktur auch für Aufträge von externen Partnern, indem wir z.B. Prozessmodule bereitstellen, Epitaxiestrukturen liefern oder Gerätedemonstratoren entwickeln und fertigen.

III-V Technology

The research area III-V technology combines know-how and resources at FBH in materials and process technology as well as mounting and assembly. These competencies form the basis for the development of devices in the photonics und III-V electronics research areas.

- ***Epitaxy nitrides*** – heterostructures for UV LEDs, UV photodetectors, violet laser diodes, and GaN transistors. These heterostructures are the basis for the respective devices at FBH. Additionally, HVPE growth processes for GaN and AlGaN substrates and templates are developed.

- ***Epitaxy arsenides*** – heterostructures for GaAs laser diodes for device development at FBH as well as for external customers. Also, SAM structures for pulsed laser systems are fabricated.

- ***Process technology*** – processes for a large variety of devices based on GaAs, InP, and GaN on wafers from 2" to 4" in diameter. These are carried out and continuously improved on a process line that is compatible with industry standards, offering high flexibility at the same time.

- ***InP devices & SciFab*** – InP HBTs for THz frequencies form the basis for FBH's THz systems. Monolithically integrated with Si BiCMOS circuits, this technology is also made available to external customers in cooperation with the Leibniz institute IHP.

- ***Mounting & assembly*** – devices are mounted onto heat sinks or into packages to allow for integration into modules and systems.

- ***Materials analytics*** – supports the development of epitaxial growth processes by characterization of heterostructures. These analysis techniques are also utilized for the development of processing and mounting steps as well as for the analysis of root causes for device failure.

We also make our technological infrastructure available to external partners for whom we carry out process modules, deliver epitaxial wafers or develop and build demonstrator systems.

Surface effects on luminescence intensity resulting from AlGaN

The compound semiconductor AlGaN is used in optoelectronic and electronic devices developed at the FBH: light emitting diodes (LEDs), laser diodes (LDs), and solar-blind photodiodes for the UV-B and UV-C spectral range as well as high electron mobility transistors (HEMTs). Especially in the composition range with medium and high aluminum content, quantum efficiency, electrical conductivity, and spatial homogeneity of the band gap are still improvable. Moreover, the knowledge about material characteristics is limited here. A continued optimization of epitaxial growth along with material characterization is therefore still important in order to achieve progress in the development of AlGaN-based devices.

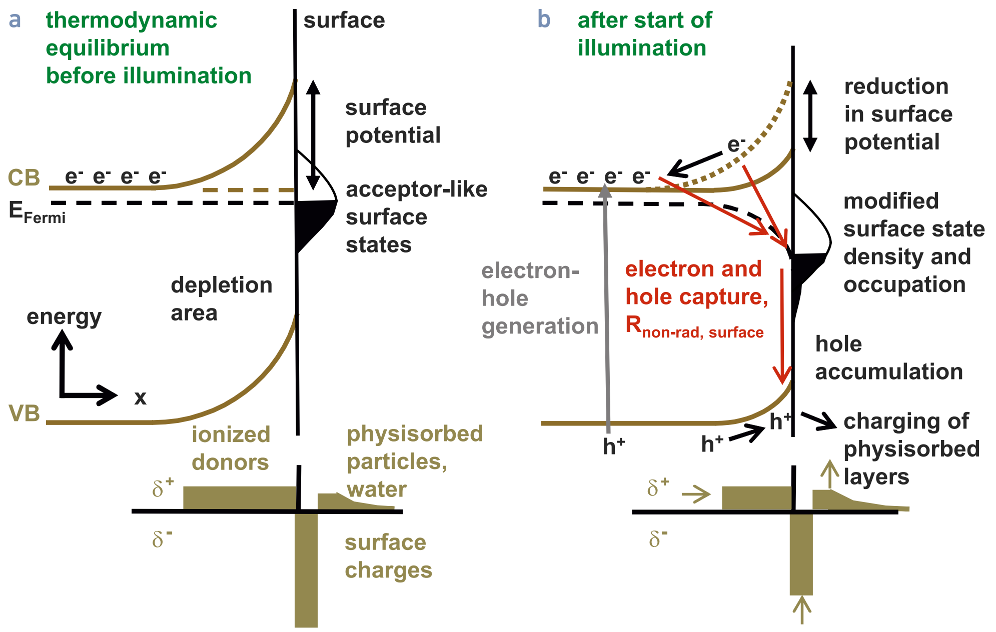


Fig. 1. Sketch of surface band bending and distribution of charges at an AlGaN surface (a) before and (b) after start of UV illumination. Photo-generated charge carriers near the surface modify the surface potential, the composition and charges of adsorbates, and the surface states.

Several characteristics of the AlGaN semiconductor, including the material composition, the spatial uniformity of the band gap in the epitaxially grown crystal, the internal quantum efficiency for UV light generation, and the strength of internal electric fields in heterostructures, can be determined by appropriately designed photoluminescence experiments. Due to a high absorption coefficient of 1 - 2 × 10^5 cm^{-1} for light with above band gap energy in nitride semiconductors, electron-hole pairs are generated near the semiconductor surface in a depth of 100 to 200 nm. In this depth, the recombination of photo-generated electrons and holes is subject to material characteristics at the III-nitride surface. The photoluminescence emission spectrum is influenced by the electric field in the surface depletion layer as well as by surface recombination processes. Emission energy, emission linewidth, and intensity of the emission peaks can be affected. Furthermore, charge carriers generated near the surface are separated by the surface field. Positively charged holes are generally accumulated at the semiconductor surface. This supply of positive charges modifies the amount of surface charges and the surface potential. Consequently, it influences the adsorbate configuration at the semiconductor surface and the velocity of surface recombination. It takes time scales up to minutes and hours before the complex system of the AlGaN surface with chemically and physically bound adsorbates, the ambient atmosphere, and the charge generation by illumination gets to equilibrium. We studied this process by photoluminescence measurements over time. We found that the temporal change in luminescence intensity strongly depends on parameters like sample temperature, power of the incident light used for excitation, doping of the semiconductor, dislocation density penetrating the surface, ambient atmosphere condition, and pretreatment of the surface. All these parameters either define the adsorbate configuration at the AlGaN surface or they modify the velocity of a possible change in the adsorbate configuration if the system is disturbed.

Instable photoluminescence intensity is detrimental for material characterization. Exact intensity measurements or comparative intensity measurements between different samples become easily incorrect. To solve this problem we capped the investigated AlGaN layers with 30 nm thick AlN layers, which provide a higher band gap than the incident light's energy in our photoluminescence experiments. The cap layer suppresses charge carrier supply to the semiconductor surface, a modification of the surface states, and a temporal change in surface recombination. Additionally, the cap layer reduces the impact of the surface field on the investigated AlGaN layer. With the AlN cap layers the luminescence intensity from the AlGaN layers becomes stable in time. A further positive effect is that the AlN cap reduces surface recombination and increases the luminescence intensity by about 40 % at room temperature.

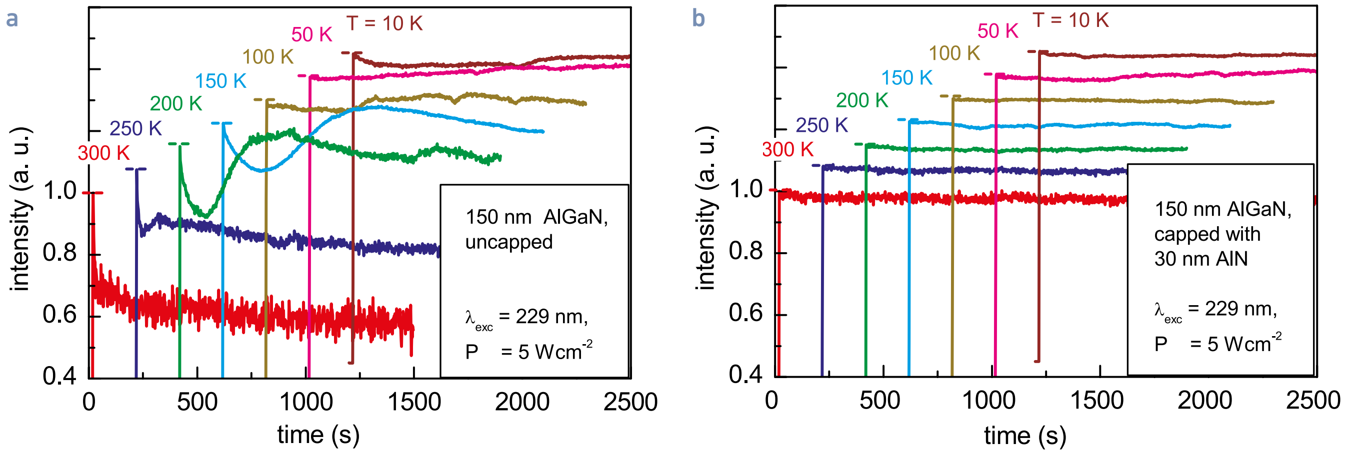


Fig. 2. Temporal change in intensity of the AlGaN band gap luminescence during UV illumination in photoluminescence experiments. An uncapped AlGaN layer (a) shows an instable intensity which strongly varies with temperature. An AlGaN layer with AlN cap (b) shows stable luminescence intensity, independent of sample temperature.

The performed studies led to several additional insights related to the semiconductor surface: a) The surface potential of III-nitrides can be manipulated strongly by doping. b) There are at least two processes with different thermal activation energies which affect the adsorbate configuration and the surface recombination in AlGaN during UV illumination. These processes cannot be specified directly by photoluminescence measurements. However, their effect on the surface recombination is accessible via intensity measurements. c) An exact adjustment of the adsorbate configuration on AlGaN surfaces is difficult. Variations of air humidity and changes in daylight during storage in an air-conditioned laboratory lead to well detectable, but not reproducible variations of the semiconductor surface. d) The change of the adsorbate configuration and the surface recombination is very fast when the surface is exposed to an ambient atmosphere containing oxygen or water. The AlGaN surface reacts to an exposure to air on time scales below one second.

The gained knowledge about surface effects will help to increase the exactness and the reproducibility of material characterization for AlGaN. In addition, the observed sensitivity of the semiconductor surface to external disturbances should raise awareness for difficulties which might occur during processing of these surfaces.

This study was supported by the German Research Foundation (DFG) within the *Collaborative Research Centre 787*.

Untersuchungen der Fotolumineszenz an AlGaN-Volumenschichten ergaben, dass sich die Intensität der Lumineszenz auf Zeitskalen von Minuten und Stunden verändert. Dieses Verhalten wird durch die oberflächennahe optische Anregung mit UV-Licht hervorgerufen. Eine derartige Bestrahlung erzeugt eine permanente Zufuhr von Ladungsträgern zur Oberfläche und beeinflusst somit Oberflächenzustände und die Oberflächenrekombination. Die Ausprägung dieses Effekts ist abhängig von Parametern, die die Konfiguration von Adsorbaten an der AlGaN-Oberfläche bestimmen: Probentemperatur, optische Anregungsleistung, Dotierung des Halbleiters, Dichte der Durchstoßversetzungen im Halbleiter, Umgebungsklima und Vorbehandlung der Oberfläche. Mittels einer 30 nm dünnen AlN-Deckschicht kann dieser Effekt unterdrückt werden, wodurch vergleichbare und reproduzierbare Intensitätswerte von AlGaN-Schichten gemessen werden können. Zusätzlich lassen sich dabei Verluste durch die Oberflächenrekombination reduzieren.

Publications

C. Netzel, J. Jeschke, A. Knauer, M. Weyers, "Avoidance of instable photoluminescence intensity from AlGaN bulk layers", Phys. Status Solidi B, 1600672 (2017).

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GaN npn structures for vertical FETs

Fast switching of high current levels is an essential prerequisite for a number of electronic and optoelectronic applications. The light output power of diode lasers, for example, can be significantly increased by electrically pulsing at high current levels without self-heating constraints. Since the switching speed critically depends on dynamic losses, the inductive loop within the switching circuit has to be minimized as far as possible. One way to address this issue is to place the switching transistor on top of the diode laser, which reduces the loop size substantially. However, hybrid integration of diode laser and transistor requires vertical transistor construction principles to accomplish a direct current flow from the transistor to the diode laser on the shortest possible way.

To demonstrate this concept, vertical GaN-based transistors with a blocking voltage of more than 300 V, a pulse current capability of 50 A, and normally-off switching behavior are developed within the German-Polish *PioneerGaN* project. This project aims to fabricate true vertical devices on low defect density GaN substrates that are produced using the ammonothermal method, thus avoiding vertical leakage currents, premature breakdown, and device degradation.

Fig. 1 shows the principal layer and device layout of the vertical MISFET. The active region of the device basically consists of a stack of n^--doped GaN followed by a p-GaN layer and an n-doped top layer. A high-quality gate insulator conformably coated onto the trench sidewall separates the gate metal from the semiconductor. As the gate is biased positively with respect to the source contacts, the semiconductor regions at the interface between the gate isolator and the p-GaN become conductive by the carrier inversion process. The electrons passing through the inversion layer are then spreading into the n^--drift layer and are finally collected by the highly conductive substrate.

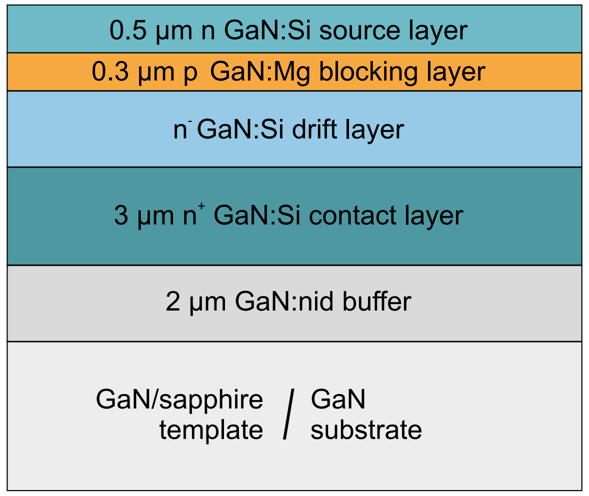

Fig. 1. Principal layer design of a MISFET device structure fabricated on sapphire and GaN substrates.

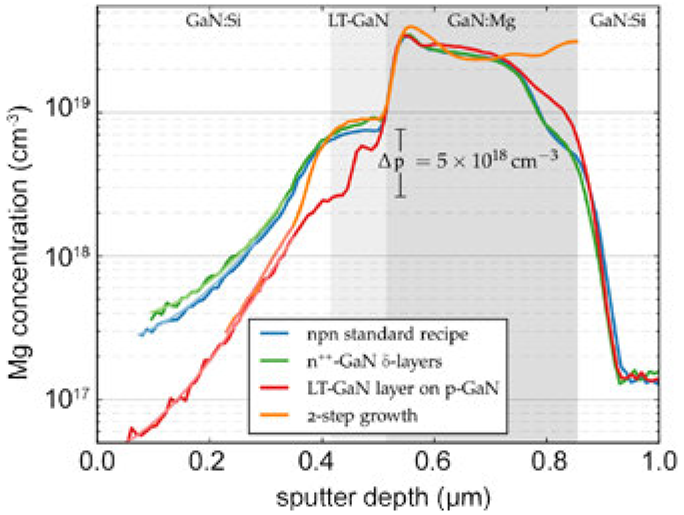

Fig. 2. Mg concentration profiles in MOVPE grown npn structures, measured by secondary ion mass spectrometry.

Development of epitaxial growth by MOVPE in the initial project phase focused on the p-doping characteristics using Cp_2Mg in an AIX200/4-RF single wafer reactor. Main challenge here is Mg carryover affecting the n-p and p-n junction definition. Using secondary ion mass spectrometry (SIMS), different approaches to minimize the Mg incorporation into the upper n-layer were studied (Fig. 2). Both the insertion of a thin highly n-type d-doped layer as well as the splitting of the growth process between the p- and n-type material with intermediate reactor cleaning could not reduce the Mg carryover as measured by SIMS. On the other hand, the n-GaN overgrowth at a reduced temperature (LT-GaN) showed a lower Mg incorporation level in the Si-doped material. Based on these results, first device test structures grown on 2-inch sapphire substrates were provided for the development of device process modules at FBH (see also p. 106).

Towards the final goal of vertical current flow, a first batch of 1-inch GaN substrates was provided by the Polish project partner SEEN. Broadening of X-ray rocking curves (full width at half maximum, FWHM) was used to evaluate the structural properties of the GaN substrates. FWHM values of 30 arcsec, 20 arcsec, and 55 arcsec for the (002), (102), and (302) reflexes, respectively, verified the low density of threading dislocations (epd density specified at around 5 x 10^4 cm^{-2}). Comparable FWHM values were measured after homoepitaxy of about 3 µm thick GaN, confirming that no extended defects are created at the substrate-epilayer interface. Fig. 3 shows the 1-inch substrate in the 2-inch susceptor pocket bordered by sapphire spacer rings. The good quality of the epi-ready surface polish was also validated by the absence of any modulation of the in situ measured reflectance as well as a constant and flat curvature transient. Surface morphology (see optical microscopy picture inset in Fig. 3) was smooth with a low waviness on about 90 % of the substrate area. Upcoming work comprises growth optimization of the n^--GaN drift layer, which limits the achievable breakdown voltage depending on layer thickness and background doping level. It is also planned to compare the MOVPE growth approach with MBE performed by the partner EIT+ in Wroclaw.

The *PioneerGaN* project is partly financed by the European Regional Development Fund (ERDF), project no. 10157776.

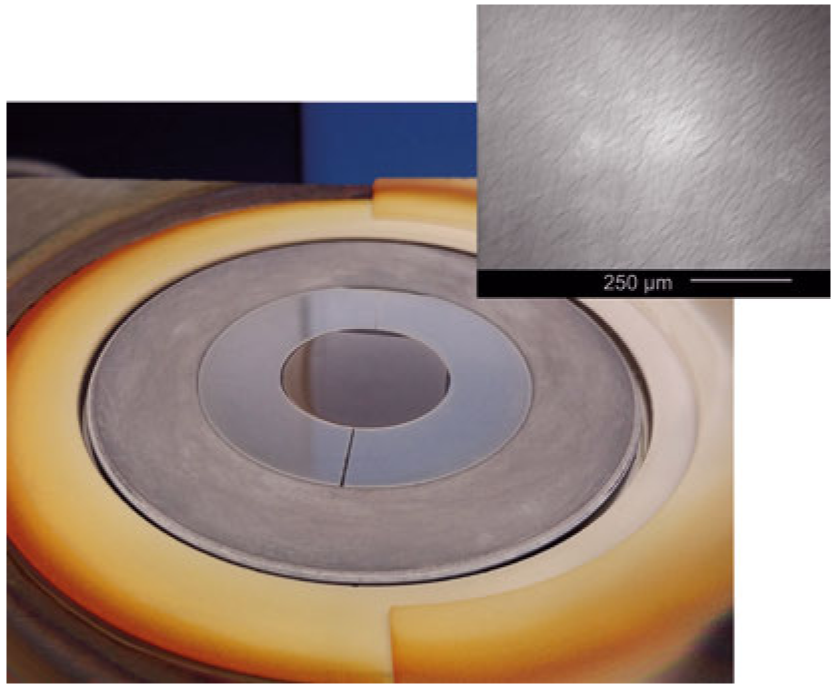

Fig. 3. Susceptor setup for MOVPE growth on 1-inch GaN substrates from SEEN/Ammono. The inset shows a typical surface morphology (optical microscopy) of GaN grown homoepitaxially on the ammonothermal substrate.

Schalttransistoren mit vertikalem Transistordesign eignen sich ideal zum schnellen Schalten hoher Ströme – eine Voraussetzung für viele elektronische und optoelektronische Anwendungen – und ermöglichen eine hybride Anordnung von Transistor und Laserdiode. In dem deutsch-polnischen *PioneerGaN*-Projekt entwickeln die Partner ein vertikales Transistorkonzept, das Durchbruchspannungen von 300 V bei einer Stromtragfähigkeit von 50 A im gepulsten Betrieb demonstrieren soll. Die Transistorstruktur besteht aus einer niedrig n^--dotierten Driftregion, einer p-GaN-Schicht und einer n^+-GaN-Schicht. Sie wird auf defektarmen GaN-Substraten hergestellt, um geringe Leckströme und eine hohe Zuverlässigkeit zu gewährleisten. Die Optimierung der Epitaxie mittels MOVPE konzentrierte sich zunächst auf die p-Dotierung von GaN mittels Cp_2Mg sowie die Minimierung des parasitären Einbaus von Mg in die benachbarten n-dotierten Schichten. Hierbei konnte die Verschleppung von Mg in die anschließende Si-dotierte Schicht durch ein Absenken der Wachstumstemperatur verringert werden. Die GaN-Substrate des polnischen Projektpartners wurden mittels Röntgendiffraktometrie hinsichtlich ihrer kristallinen Perfektion charakterisiert und in der MOVPE überwachsen. Die gemessenen Halbwertsbreiten (z.B. ~55 arcsec für den (302)-Reflex) bestätigen die vom Hersteller Ammono spezifizierten geringen Versetzungsdichten (epd ~5 x 10^4 cm^{-2}). Die verspannungsfreie Epitaxie der Transistorstruktur auf den GaN-Substraten führte zu keiner Verbreiterung der XRD-Halbwertsbreiten.

Development of monolithic optical microsystems for the stabilization of light sources for quantum metrology

Photonic Integrated Circuits (PICs) are attracting increasing interest in many aspects of modern technology due to their versatility. They are not only the backbone of all optical networks, but have also demonstrated their capability as sensors for applications in highly corrosive environments: acceleration and motion sensors as well as biosensors. Basic building blocks for optical microsystems are waveguides to direct light due to internal reflection, couplers to distribute light between different waveguides, and resonators to produce narrow-band frequency filters. Waveguides have to be very small with cross sections of around 1 µm^2 to be single mode or to support a few modes only. At FBH, a process has been developed that allows the fabrication of such microstructures in silicon dioxide on silicon.

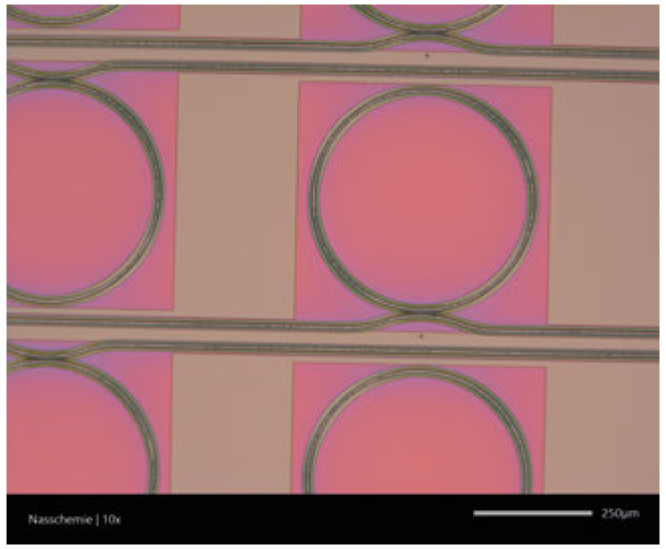

Fig. 1. Photomicrograph of a production-friendly ring resonator – waveguide design with high quality factor and small linewidth.

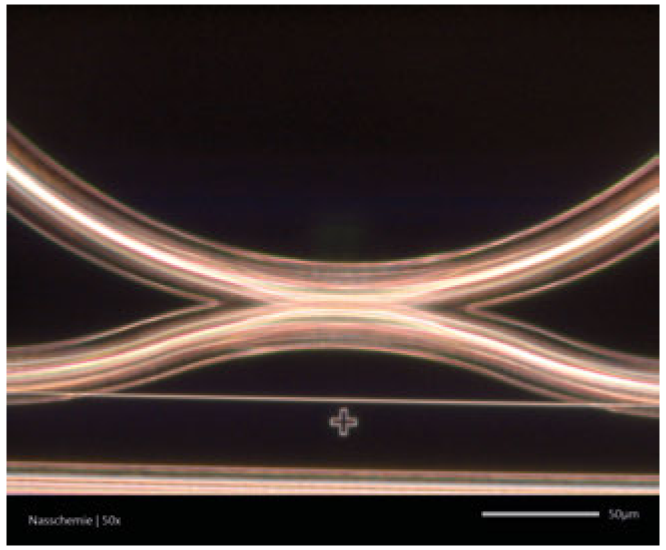

Fig. 2. Detail of the coupling region of the optical microsystem imaged by dark field optical microscopy; waveguide structures and trench light up.

Classical materials for fiber waveguides are glass and quartz. These materials show very low absorption in the visible and near infrared range of light; and such fibers are available since the 1970s. However, they have an index of refraction below that of conventional semiconductor materials such as silicon, GaAs, and InP. Consequently, a waveguide located on top of a semiconductor chip will not work as the light will be absorbed by the semiconductor. This traditionally impedes using them in complex monolithically integrated optical microsystems.

Nevertheless, FBH has succeeded in on-chip integration of an optical micro resonator interfaced with a waveguide in silicon dioxide on silicon, as shown in Figs. 1 and 2. Common 3" silicon wafers coated with silicon dioxide are used for chip fabrication. By means of a special process flow, the silicon substrate below the silicon dioxide waveguide is removed – in a manner that the waveguide becomes part of a suspended membrane or a jib and the propagation of light is not disturbed by the strongly absorbing silicon. To accomplish the removal of the base material, many holes or long trenches are formed parallel to the waveguide, which allows selective etching of the base material.

The overall process flow comprises four lithographic layers and allows the combination of high-resolution electron beam lithography and stepper lithography. In a first layer, overlay and alignment structures are created. In a second lithography step, the chamfer of the waveguides is formed and then etched by fluorine-based reactive ion etching. The next step is the formation of the waveguides and resonators, which is accomplished by lithographic pattern formation and carefully balanced plasma etching. The last step is a robust lithographic process that defines the trench for wet chemical under etching of the silicon dioxide to remove the silicon using a mixture of hydrofluoric acid, nitric acid, and acetic acid.

Design and process need to be evened out delicately. The wet etch process of the silicon is not 100 % selective with respect to silicon dioxide. Extended etching times to remove several micrometers of silicon significantly affect the thin membrane and the waveguide. Hence, the delicate waveguide structures have to be protected by a photoresist layer. Most importantly, the chip design has to be optimized to reduce the etch time needed and to avoid any spots that require a particularly prolonged etching.

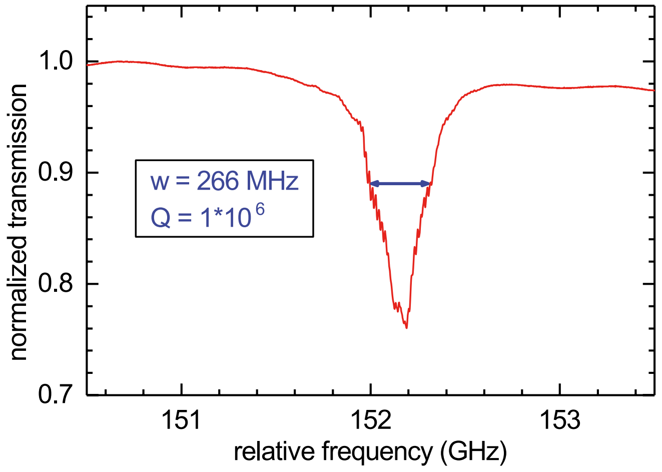

Fig. 3. Optical characterization of a ring resonator – waveguide system at a wavelength of 1064 nm. A quality factor of 10^6 and a linewidth of only 266 MHz were obtained.

The fabricated systems were optically characterized with a tunable laser at a wavelength of 1064 nm. A typical result is shown in Fig. 3. A quality factor of about 10^6 with a FWHM of only 266 MHz was measured for a coupler with a membrane height of 500 nm, a coupling distance of 800 nm, and a waveguide and ring width of 1600 nm. The results confirm that ring and disk resonators with a size of a few hundred micrometers can show quality factors better than 10^5 and a very narrow linewidth of a few 100 MHz only. They are therefore ideally suiting the purposes of the advanced optical communication technology.

These results prove the concept of on-chip integration of optical systems in silicon on silicon dioxide, paving the way for further developments towards PICs for advanced optical communication technology and evolving quantum technologies.

This work was accomplished in the framework of the project *Integrated micro resonator stabilized light source for quantum metrology*, supported by the European Regional Development Fund via the *Pro*FIT program of Investitionsbank Berlin (IBB 101 594 65).

Am FBH wurde eine Technologie zur Herstellung von optischen Mikrosystemen im Materialsystem Siliziumdioxid auf Silizium entwickelt. Die optische Charakterisierung der Mikroringresonatoren, die mit einem integrierten Lichtwellenleiter gekoppelt wurden, ergab einen Qualitätsfaktor von 10^6 und eine Halbwertsbreite von 266 MHz. Damit konnte das Konzept der On-Chip-Integration derartiger Mikrosysteme erfolgreich nachgewiesen werden. Die Ergebnisse sind die Grundlage für weitere Entwicklungen im Bereich der optischen Kommunikations- und Quantentechnologien.

Der Prozess selbst umfasst vier lithografische Ebenen und erlaubt es, Elektronenstrahllithografie und optische Lithografie zu kombinieren. Nach Herstellung von Alignment- und Overlaystrukturen sowie der Facettenätzung werden Wellenleiter und Resonatoren in einem Plasmaätzschritt geformt. Das Entfernen des Basismaterials unter den optischen Strukturen erfolgt dann in einem nasschemischen Ätzschritt.

Chip mounting technology for 300 - 500 GHz applications

Recent advances in the realization of millimeter-wave (mm-wave) semiconductor components have pushed the operating frequency of electronic chips towards one terahertz. The use of mm-wave frequencies in commercial applications such as high resolution robotic radar, material imaging, and security scanners is hampered, however, by the dearth of reasonably priced active component semiconductor chips and the cost of the currently used split-block mm-wave packaging and subsystem integration techniques.

To overcome these problems, we have designed and fabricated multichip assemblies of mm-wave passive and active electronic chips on specially designed RF carrier boards, along with scalable flip-chip mounting [1]. When moving the integration interface from the package level, i.e., the split block, to the chip and board level, significant savings in assembly cost and a substantial reduction in subsystem size and weight can be achieved.

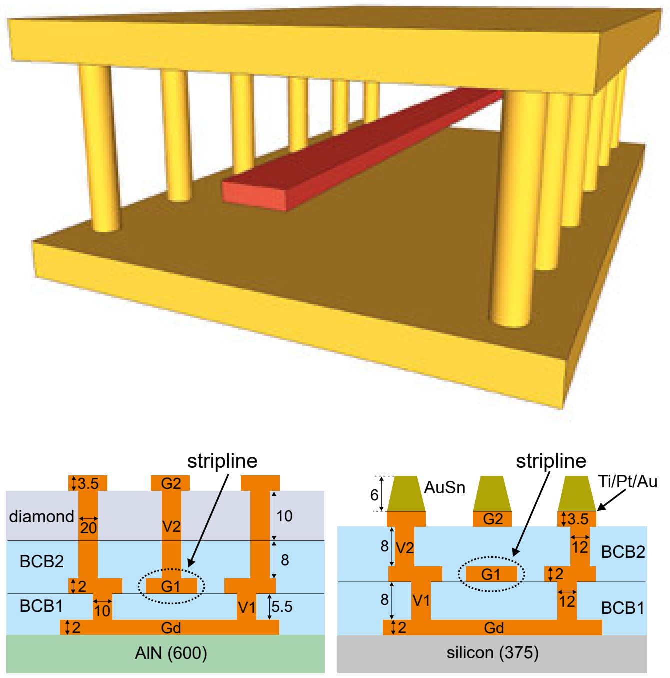

Fig. 1. Conceptional drawing of shielded line architecture realized with three interconnect layers and ground-connecting vias (top) and cross-sectional schematic of chip (bottom left) and submount (bottom right) wiring levels and interconnect vias (dimensions in µm).

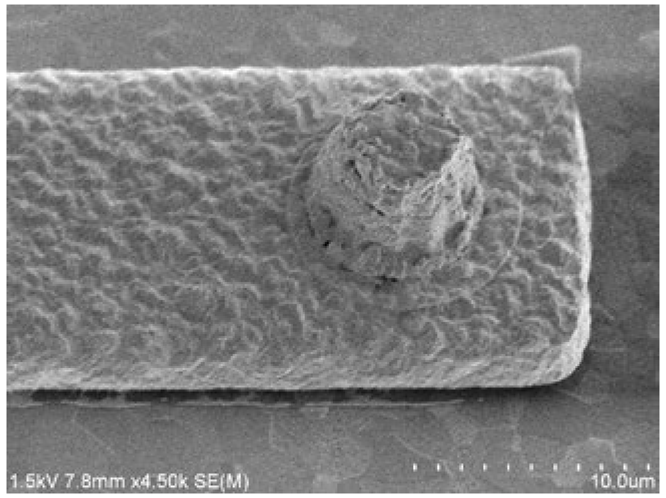

Fig. 2. Scanning electron micrograph of 10 µm diameter bump on electroplated line.

On-chip low-loss RF lines operating at 500 GHz can be designed with 10 µm design rules, and chip-to-board placement accuracy better than 1 µm can be achieved with modern flip-chip equipment. The concept of using flip-chip technology is thus well-suited for mm-wave multichip packaging, as opposed to the traditional wire bond assemblies which introduce loop inductance and fabrication tolerances that are magnitudes higher.

The main idea of our approach is to contain the propagating wave within a thin-film waveguide structure on the active chip and carrier board, as well as within a carefully engineered flip-chip transition. As a result, we achieve a manufacturable planar architecture akin to printed circuit board assemblies. This approach alleviates the need for ultrathin chips with thicknesses well below 50 µm. Applying a shielded stripline approach on the RF chip as well as the RF carrier substrate, in addition to using a carefully designed quasi-coaxial flip-chip transition, allows extending the usable frequency range of planar RF connections to 500 GHz [2]. Ground layers are placed both above and below the signal stripline waveguide. A cross section of the shielded stripline geometry is shown in Fig. 1.

Both chip and submount structures are fabricated in conventional III-V semiconductor processes on 3-inch substrates. The use of i-line stepper lithography in fabrication of all conductive layers and vertical interconnects on both the chip and the submount results in very high structure fidelity and uniformity. As opposed to contact lithography, the stepper's projection lithography avoids patterning problems related to sample height variation stemming from resist edge beads, particle defects, and other sources. The interconnect layers were formed by gold electroplating with metal thicknesses ranging from 2 to 3.5 µm. The vertical vias within the submount and the chips were realized with fluorine-based plasma etching [3]. Both the chip and the submount included three layers of metallization, with the top and bottom layers serving as shielding ground layers and the middle layer holding the stripline conductor.

Miniaturized $Au_{80}Sn_{20}$ bumps of 10 µm diameter and a total thickness of 6 µm were structured in a lift-off process. A scanning electron micrograph of a miniaturized bump on top of an electroplated signal line is shown in Fig. 2. The flip-chip assembly is carried out using an FC-150 semiautomatic bonder with the chuck temperature set between 320 °C and 350 °C.

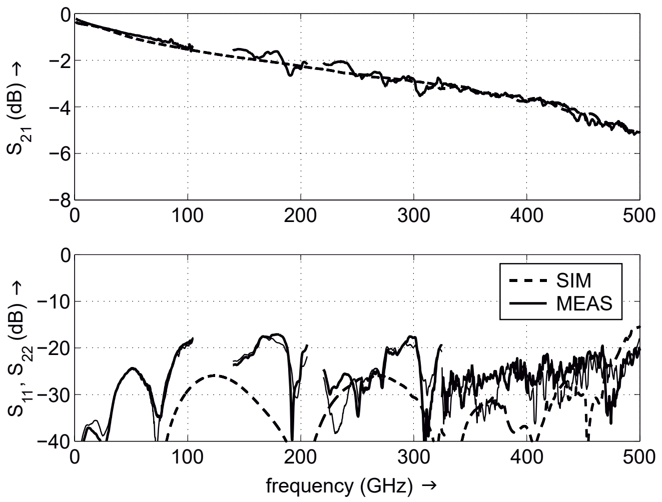

Fig. 3. Scattering parameters S_{21}, S_{11}, and S_{22} from on-wafer measurement (solid line) and 3-D EM simulation (dashed line) of four flip-chip transitions connected back-to-back.

The fabricated flip-chip assemblies containing back-to-back bump interconnects were characterized up to 500 GHz in S-parameter measurements. Fig. 3 shows good agreement between measured and simulated (3-D EM) scattering parameters of four stripline-to-stripline flip-chip transitions with a total length of 1.8 mm. Each of the two striplines on the MMIC has a length of 160 µm. At 500 GHz, this structure exhibits an insertion loss value of around 5 dB, which means around 1 dB per transition (excluding the stripline propagation loss, which amounts to 2 dB/mm at 500 GHz). Return loss values are larger than 18 dB from DC to 500 GHz.

This work was supported in part by the German Ministry of Research within the VIP project *AVTE* under project no. 03V0060 and in part by the German National Aeronautics and Space Research Centre under project *MIMIRAWE*.

Elektronische HF-Schaltungen, die auf dem Verbindungshalbleiter InP basieren, erreichen mittlerweile Arbeitsfrequenzen bis 1 THz. Sie eigenen sich damit für Anwendungen wie etwa hochauflösendes Radar für die Robotik, Materialuntersuchungen, Sicherheitsscanner und die drahtlose Breitband-Kommunikation. Um jedoch THz-Komponenten und -Systeme kostengünstig im industriellen Maßstab herzustellen, müssen neue Wege für die Aufbautechnologie gefunden werden. Die bislang verwendeten Split-Block-Aufbauten sind in der benötigten präzisen mechanischen Herstellung sowie in der Montage der THz-Halbleiterchips sehr kostenaufwändig. In unserem Ansatz werden THz-Chips im Flip-Chip-Verfahren auf spezielle HF-Trägersubstrate montiert. Sowohl die HF-Verbindungsleitungen auf dem Chip und dem Trägersubstrat als auch die vertikale HF-Verbindung zwischen Chip und Substrat sind durch optimale Abschirmung und verlustarme Metallisierung (Gold) für Frequenzen bis 500 GHz einsetzbar. Die nötigen Strukturen auf Chip und Substrat lassen sich in bewährten III/V-Halbleiterprozessen reproduzierbar und durch parallele Prozessierung in einem skalierbaren Maßstab herstellen. Eine Einfügedämpfung von unter 1 dB bei 500 GHz wurde damit erreicht.

Publications

[1] N. Weimann, S. Monayakul, S. Sinha, F. J. Schmückle, M. Hrobak, D. Stoppel, W. John, O. Krüger, R. Doerner, B. Janke, V. Krozer, W. Heinrich, "Manufacturable Low-Cost Flip-Chip Mounting Technology for 300-500-GHz Assemblies", IEEE Trans. Compon. Packag. Manuf. Technol., vol. 7, no. 4, pp. 494-501 (2017).

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Progress in InP-HBT device technology and circuit fabrication

The development of electronic circuits for applications in the electromagnetic spectrum between 100 and 1000 GHz is rapidly advancing. The best performing circuits demonstrated so far with operating frequencies above 300 GHz are realized in heterostructures based on the compound semiconductor InP and the lattice-matched materials InGaAs/InAlAs and GaAsSb. FBH is pursuing the development of InP heterobipolar transistors (HBTs), which are well-suited for RF power applications compared to their unipolar planar counterpart, the InP high electron mobility transistor (HEMT). Relatively complex circuits can be made in HBT technology owed to its relatively compact vertical transistors. As an example, a frequency quadrupler operating at 330 GHz [2] is shown in Fig. 1. A power amplifier with 23 dBm output power across 10 GHz bandwidth has also been demonstrated [3].

Moreover, the InP HBT can be monolithically integrated with silicon (Si) technology, resulting in circuits with high functional complexity and excellent RF performance at the highest frequencies [1, 4]. FBH and the Leibniz institute IHP are continuing to develop a heterointegrated InP HBT/SiGe BiCMOS platform. Recent advances include the decrease of emitter width from 800 to 500 nm, leading to reduced junction capacitance and hence higher cut-off frequencies. The reduction in emitter width was made possible by new process developments: a new *i*-line stepper lithography module combined with optimization of FBH's electron beam metal deposition equipment resulted in reproducible fabrication of half-micron emitter structures. Further emitter scaling is currently pursued with the use of electron beam lithography, enabling emitter widths of 200 nm with FBH's shaped-beam equipment.

The addition of precision thin-film resistors to the InP MMIC stack, which includes three gold metal levels with BCB interlayer dielectric and low-loss thin-film capacitors besides the active HBT devices, allowed us to realize broadband circuits such as traveling wave and transimpedance amplifiers. The resistor values are accurate to less than 2 %, enabling high quality impedance matching.

With the number of lithography layers exceeding 20, the InP HBT fabrication process represents the highest processing complexity of FBH's compound semiconductor technologies. This complexity leads to challenges in particle control and process module stability in a shared fabrication environment such as FBH's cleanroom. Device stability and reliability are indispensable when moving from single devices or circuits to system demonstration and industrial prototyping. Compared to silicon, compound semiconductor technologies suffer from the lack of a stable surface oxide. The passivation of active device surfaces is paramount to stable device operation. We recently replaced the organic encapsulation (benzocyclobutene) of the HBT's emitter-base junction with an inorganic material, silicon nitride (SiN_x) deposited in an inductively coupled plasma system at low temperature (≤ 80 °C). A cross section of a SiN_x-passivated InP HBT sidewall is shown in Fig. 2. In combination with a suitable surface pre-treatment, the parasitic base recombination currents could be minimized. Furthermore, the new junction passivation does not deteriorate under high-current stress. We measured repeatable stable DC current gain for more than 100 hours under stress conditions (see Fig. 3).

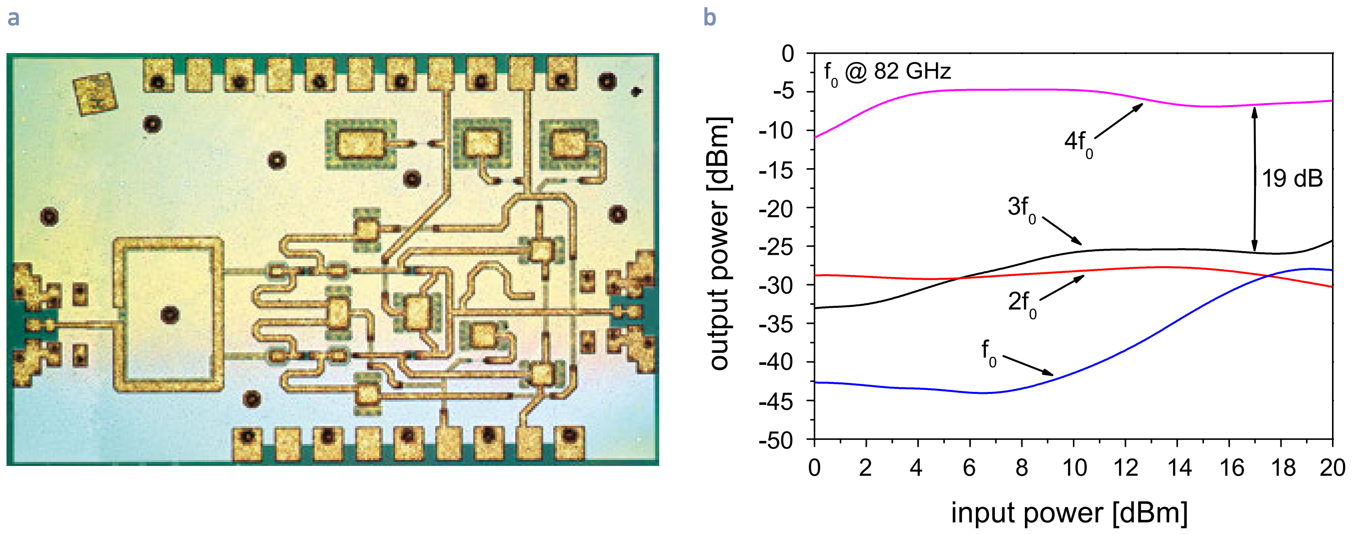

Fig. 1. Frequency Quadrupler MMIC (a) using an 800 nm InP DHBT realized in transferred substrate technology; results for the output power (b).

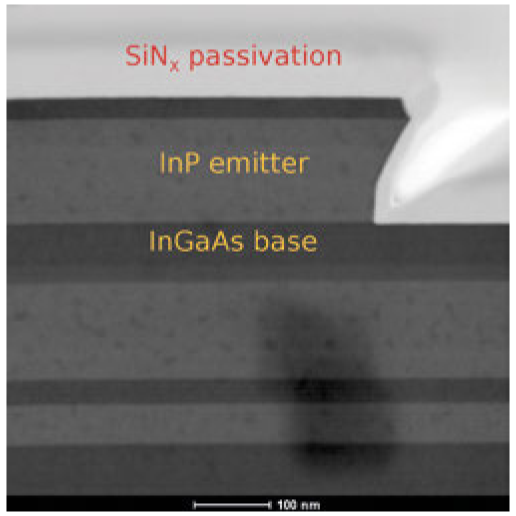

Fig. 2. STEM cross section to verify step coverage of silicon nitride passivated emitter sidewall.

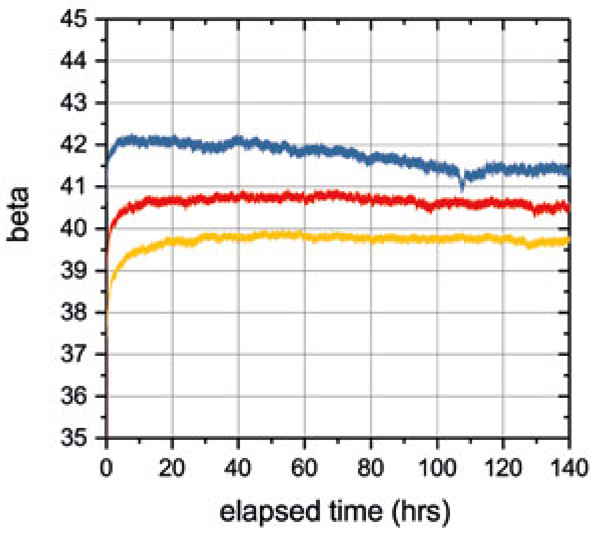

Fig. 3. Current gain vs. stress time of three heterointegrated 0.8 x 6 µm² InP-HBTs under typical operating conditions (V_{CE} = 1.5 V, I_C = 10 mA).

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Höchstfrequenzschaltungen für das Frequenzspektrum zwischen 100 und 1000 GHz entwickeln sich derzeit rasant weiter. Für Frequenzen über 300 GHz lassen sich die besten Resultate mit Transistor-Heterostrukturen erreichen, die auf Indiumphosphid (InP) basieren. Sowohl unipolare, Feldeffekt-basierte InP-HEMTs (High Electron Mobility Transistors) als auch InP-HBTs (heterobipolare Transistoren) erreichen mittlerweile Grenzfrequenzen um 1 THz. InP-HBTs werden am FBH kontinuierlich zu höheren Frequenzen weiterentwickelt, wobei die Heterointegration mit Silizium-BiCMOS-Wafern zur Realisierung komplexer mm-Wellen-Chips eine große Rolle spielt. Neben der Bauelement-Performanz muss die InP-Technologie zudem ausreichend stabil und zuverlässig sein, damit sie bei industriellen Prototypen eingesetzt werden kann. Zu diesem Zweck wurden am FBH unter anderem geeignete Passivierungsschichten entwickelt und in den InP-HBT-Gesamtprozess integriert.

Publications

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Assembly of 1200 µm aperture broad area lasers as reliable building blocks for high-energy solid-state laser pump sources

Fig. 1. Exactly aligned laser chip (p-down) and two spacers soldered in parallel on the lower CuW heatsink of a stack element (right). Diode laser stack built on 13 stack elements (left).

High-performance pump sources are required for rapidly emerging high-energy class diode-pumped solid-state lasers (HEC-DPSSLs). HEC-DPSSLs operate with ns …fs pluses, pulse energies > 1 J and average powers of several hundred watts. They are in strong demand both in industry and basic research for applications including laser shock peening and studies in material science, attosecond spectroscopy, and laser fusion. The performance of HEC-DPSSLs is limited by the characteristics of the available diode pump sources, with highest power, brightness and efficiency at lowest costs needed. In practice, the pulse width of the diode lasers operated in quasi continuous wave (QCW) mode must be tailored to match the upper state life time of the solid-state crystal in use. For example, commercial multi-kW QCW diode pump sources operate at pulse width τ = 1 ms for pumping Yb:YAG amplifiers and are limited to maximum repetition rates around ν = 10 Hz, corresponding to a duty cycle dc = 1 %. To meet further demands regarding average powers of HEC-DPSSLs in science and industry, repetition rates ν > 100 Hz corresponding to duty cycles dc > 10 % are necessary.

FBH has developed diode pump sources for such improved HEC-DPSSLs which are substantially brighter than conventional laser bars. These HEC-DPSSLs are using stacks of tailored single emitters with wide lateral aperture of 1200 µm and operation at λ = 940 nm. The single emitters were packaged in a 'sandwich' configuration into a double side passive heat sink and were cooled efficiently from the device edges. Each sandwich mount is used as a building block (stack element) to form a diode laser stack (see Fig. 1). This approach prevents inefficient rear-edge cooling in current commercial pump sources systems and avoids the expense and reliability risk of micro-channel-based cooling. A stack of 28 single emitters allows ~ 3 kW peak output power and efficient (~ 60 %) operation up to $\nu \geq$ 200 Hz (τ = 1 ms) and $dc \geq$ 20 % [2]. For example, in their recently completed collaboration with the Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy (MBI) [1], the FBH developed, fabricated, and delivered six pump modules for use as pumps for a Yb:YAG thin disk laser system. These 6 kW pump modules each included two diode laser stacks consisting of 28 stack elements. Overall, more than 336 stack elements had to be assembled, tested, and integrated. After assembly, no repair or replacement of single stack elements is possible. Any errors in orientation or location of the emitters in the stack elements will accumulate, potentially lowering the performance of the diode pump source and the HEC-DPSSL.

All chips were fabricated and assembled at the FBH. For this purpose, efficiency-optimized extreme double-asymmetric super large optical cavity (EDASLOC) vertical structures were realized by metal organic vapor phase epitaxy and processed into laser structures using standard FBH techniques [2] to form 12 mm wide laser bars with a cavity length of L = 6 mm. Facets were passivated and coated with a reflectivity of R_f = 0.9 % and R_r = 96 % at the front and the rear side, respectively. The bars were cleaved into single emitter laser chips with an aperture of w = 1200 µm and a chip width of 2 mm. These laser chips were fully automatically bonded to form stack elements using a Ficontec BL 2000, a high-performance bonding system. Laser chips (p-down) and two spacer elements were soldered using Au/Sn onto a CuW heat sink. Die attach with active alignment and 6 axis alignment of chip to heatsink combined with automated optical facet inspection enables efficient and high-precision manufacturing of the lower side of the stack elements (see Fig. 1). The upper side of the stack elements is then Au/Sn soldered with a second CuW heat sink to form a sandwich configuration, with packages processed in batches in a hydrogen atmosphere soldering furnace to form the completed stack elements.

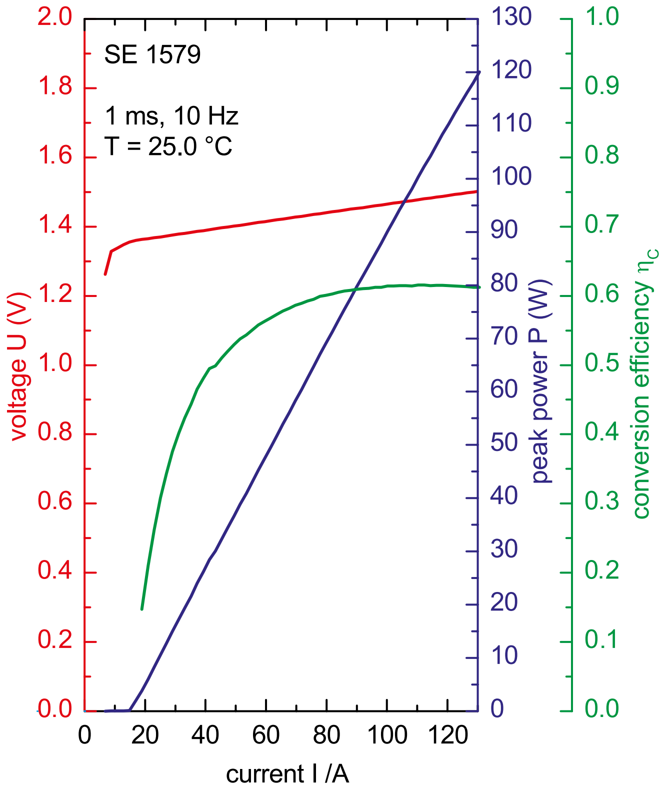

Fig. 2. Electro-optical characteristic of a typical stack element in QCW mode with P_{opt} = 120 W and η_c > 60 %.

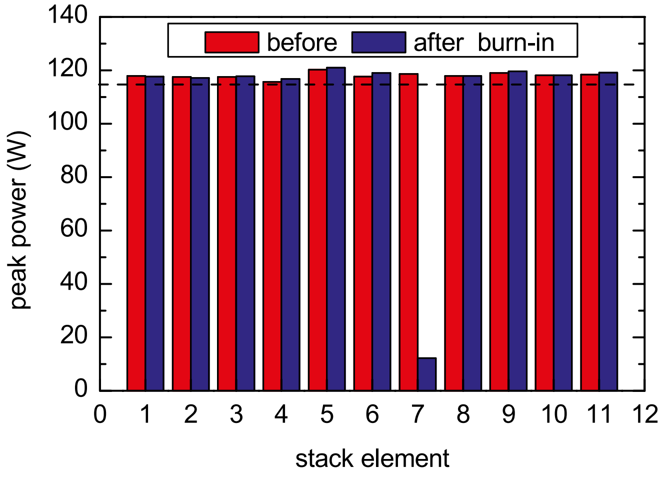

Fig. 3. Optical output power of a series of stack elements after assembly (red bars) and after approx. 6 M shot burn-in (blue bars). The criterion of exclusion of faulty stack elements (P_{opt} = 115 W) is indicated by the dashed line.

To make sure that only faultless stack elements are integrated into diode laser stacks, all stack elements were checked by optical inspection, electro-optical measurements, and a burn-in at this stage. As depicted in Fig. 2, stack elements operate with an optical output power P_{opt} = 120 W at a current of I = 130 A (τ = 1 ms, ν = 10 Hz) with a conversion efficiency η_c > 60 %. On re-test post-burn-in, as shown in Fig. 3 for one exemplary test batch, one of 11 stack elements was found to fail below the target power and was scrapped.

After burn-in, stack elements are soldered to form a diode laser stack consisting of 28 emitters with a vertical spacing of 3.16 mm. DCB coolers were mounted on both edges of the stack elements, resulting in a thermal resistance of a single stack element of 1.7 K/W (simulation). The subassembly is completed by the attachment of fast-axis collimation (FAC) lenses to the stack elements. For a complete pump module, the outputs of the diode laser stacks subassemblies are optically combined into a fiber. The resulting fiber coupled modules are suitable for use in highly brilliant, high-power pump applications, for example as in the collaboration between the FBH and the MBI.

Publications

[1] R. Platz, B. Eppich, J. Rieprich, W. Pittroff, G. Erbert, P. Crump, "High duty cycle, highly efficient fiber coupled 940-nm pump module for high-energy solid-state lasers", High Power Laser Sci. Eng., vol. 4, e3 (2016).

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Dioden-gepumpte Festkörperlaser, die mehrere Joule Pulsenergie liefern, sind in wissenschaftlichen und industriellen Anwendungen zunehmend gefragt. Entsprechend steigt der Bedarf an geeigneten Pumpquellen. Das FBH hat Diodenlaserstacks entwickelt, die aus 28 identischen Stackelementen bestehen – sechs dieser Stacks können beispielsweise optisch zu einer Pumpquelle gekoppelt werden. Einige Hundert dieser Stackelemente werden benötigt, die jeweils aus einem brillanten, hocheffizienten Breitstreifenlaser mit einer Wellenlänge von 940 nm und 1200 µm Apertur bestehen. Eine besondere Herausforderung ist hierbei, dass die Stackelemente, nachdem sie integriert wurden, weder repariert noch ausgetauscht werden können. Justagetoleranzen summieren sich und können die Kenndaten des Stacks beeinträchtigen. Das FBH hat einen Aufbauprozess für Stackelemente entwickelt, bei dem die Laser mit einem Lötautomaten hochpräzise auf CuW-Submounts gelötet werden. Eine weitere CuW-Wärmesenke wird anschließend als eine Art Deckel montiert. Ein Testverfahren inklusive Burn-in stellt sicher, dass nur einwandfreie Stackelemente zu Stacks verlötet werden.

For further information:

https://www.fbh-berlin.com/research/iii-v-technology

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MHz

τ

ns

AlGaN

SiN_x

RF

pm

CP_2Mg

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