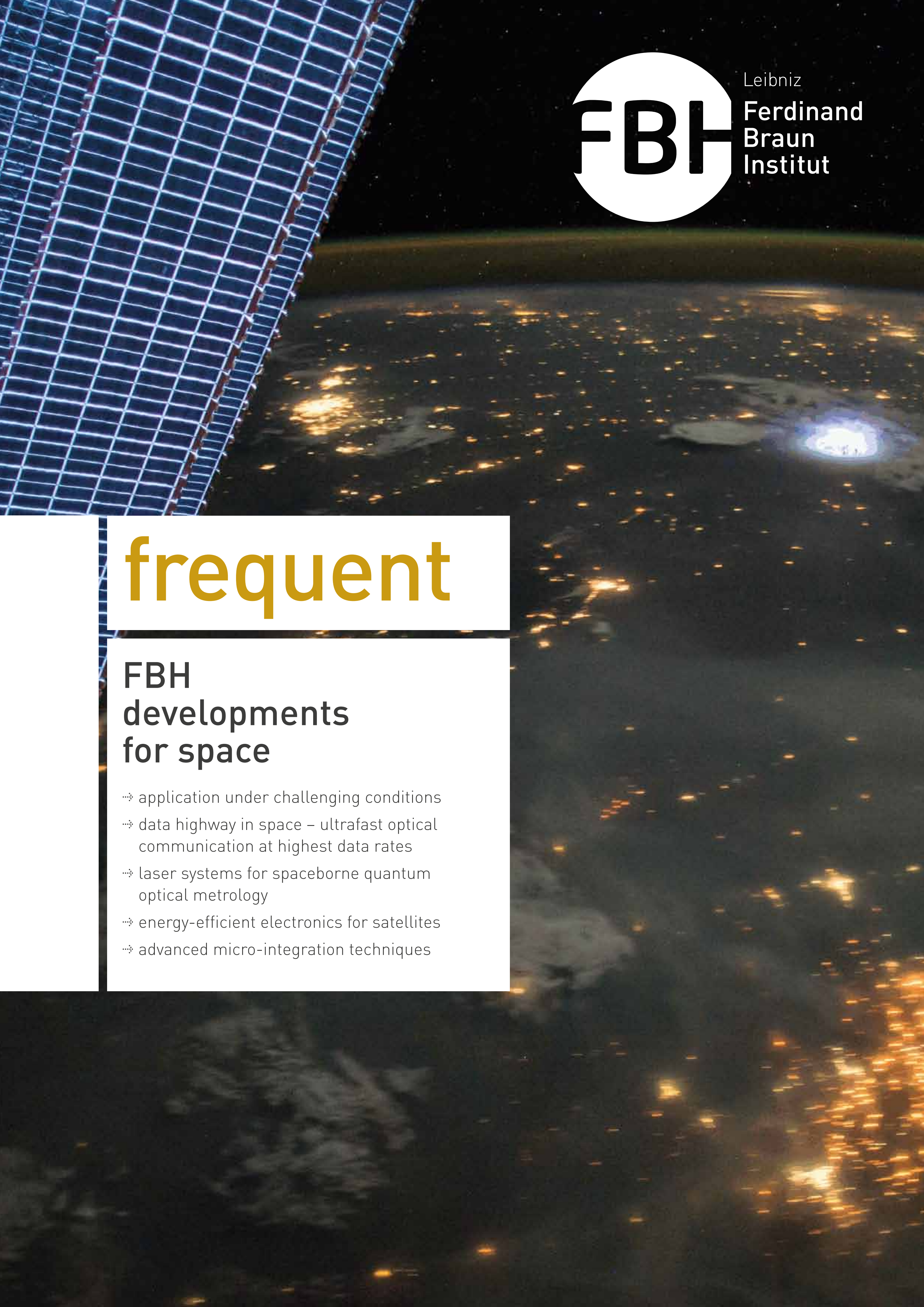

Leibniz
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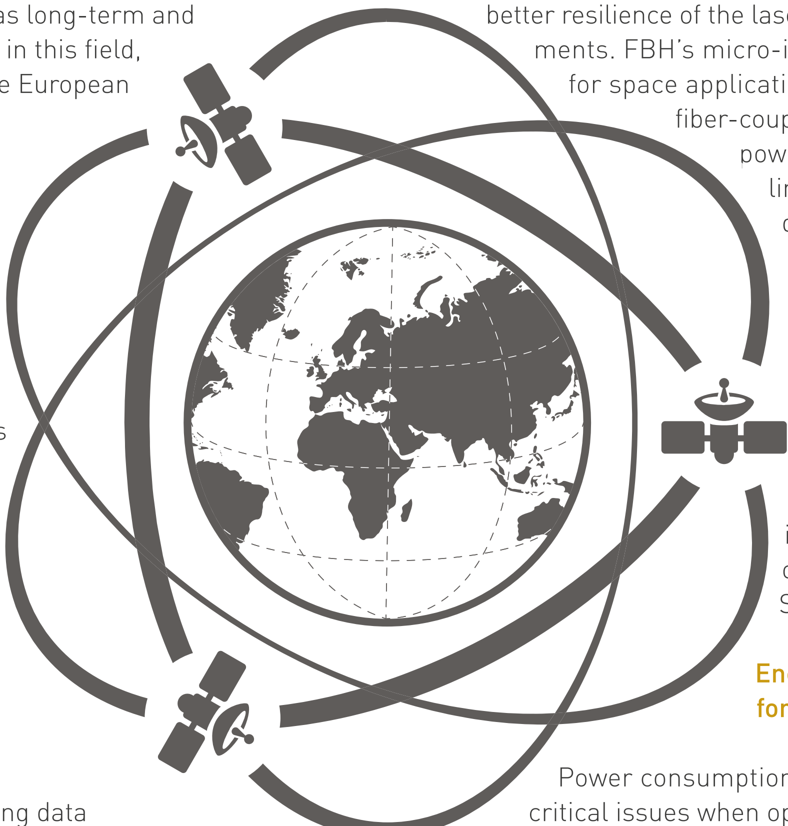
frequent

FBH developments for space

- application under challenging conditions
- data highway in space – ultrafast optical communication at highest data rates
- laser systems for spaceborne quantum optical metrology
- energy-efficient electronics for satellites
- advanced micro-integration techniques

FBH developments for space – application under challenging conditions

The communication between satellites and earth is truly demanding with respect to the related technical requirements: Devices need to be particularly reliable and robust so that they can survive a rocket launch and work properly under the harsh conditions in space (radiation, thermal variations). FBH laser benches, for example, still work flawlessly on board of several communication satellites since 2008. The institute has long-term and comprehensive experience in this field, working in projects with the European Space Agency ESA and the German Aerospace Center DLR. A variety of R&D projects deal with spaceborne technologies, including optical communications, quantum optical metrology, beam steering technologies and energy-efficient electronics for satellites. At the same time, FBH components developed for space are technology drivers for a multitude of terrestrial applications.



Optical communications – from earth to space

Driven by the ever-increasing data traffic, optical communication technology is going to conquer space. Therefore, ESA introduced the European Data Relay System (EDRS), a space data highway supporting real-time data links for earth observation satellites, scientific missions or high flying aircrafts with global, ubiquitous coverage. Tesat-Spacecom supplies the required laser communication terminals that enable 1,000 times higher frequency and thus much higher transmission rates than conventional radio-based communication. Moreover, laser beams can be directed at low divergence over long distances, which allows for low-error detection and protection of sensitive data. Ferdinand-Braun-Institut contributes the required sophisticated semiconductor pump sources offering highest robustness, reliability, and low-noise properties.

Laser systems for spaceborne quantum optical metrology

Since 2008, FBH has been developing and delivering miniaturized laser modules for experiments under micro-gravity conditions – in a drop tower as well as on board sounding rockets. Within a consortium of German research labs, FBH has successfully flown several laser modules during three distinct sounding rocket missions – among them MAIUS, where the first-ever Bose-Einstein condensate in space was created.

During this time span, FBH has been constantly improving its diode laser and hybrid micro-integration technology, thus advancing electro-optical performance and achieving better resilience of the laser modules to harsh environments. FBH's micro-integrated laser modules for space applications are fully packaged, fiber-coupled, and deliver high output power together with narrow linewidth. They have been designed for very high-performance precision experiments and coherent communications on satellites – including upcoming missions as part of an iodine-based frequency reference on a sounding rocket and for deployment into a cold atom laboratory on the International Space Station (ISS).

Energy-efficient electronics for satellites

Power consumption and dissipated power are critical issues when operating solid-state power amplifiers (SSPAs) in space. Envelope tracking (ET) is a well-known efficiency enhancement technique for SSPAs modulating the supply voltage of the RF power amplifier (PA) in accordance to the instantaneous signal envelope. One of FBH's ESA-funded projects deals with a reverse buck topology targeting satellite applications in the L-band. The challenge behind this topology is that it requires a floating-ground RF PA. Prototypes achieve already promising results. For future wideband systems in the 18...20 GHz range, FBH researchers investigate an alternative ET solution with excellent efficiency, which is discrete supply modulation, also known as class G.

FBH has also been working on decentralized PAs and receivers based on GaN which are required for beam steering and phased-array radar systems. This includes a European satellite project aiming at beam steering techniques for 30 GHz uplink and 20 GHz downlink communication. In addition, FBH´s normally-off power transistors are currently undergoing comprehensive stress tests to be implemented in future spaceborne electronic power conditioners.

Editorial

FBH develops sophisticated electronic and optoelectronic semiconductor devices for a wide range of applications, from chips through hybrid-integrated modules to prototypes and small-scale series. Our components are key enablers addressing the needs of today's society in fields like communications, energy, health, and mobility. Developments for space are one of our major, yet particularly challenging application fields since the devices face enormous mechanical stress during rocket launch and strains resulting from the harsh environment in space. Meanwhile, Ferdinand-Braun-Institut has a proven track record in this field, contributing with its reliable, highly capable pump laser benches used in Tesat-Spacecom's laser communication terminals to EDRS, the European data highway in space, as well as with its power amplifiers to energy-efficient electronics for satellites.

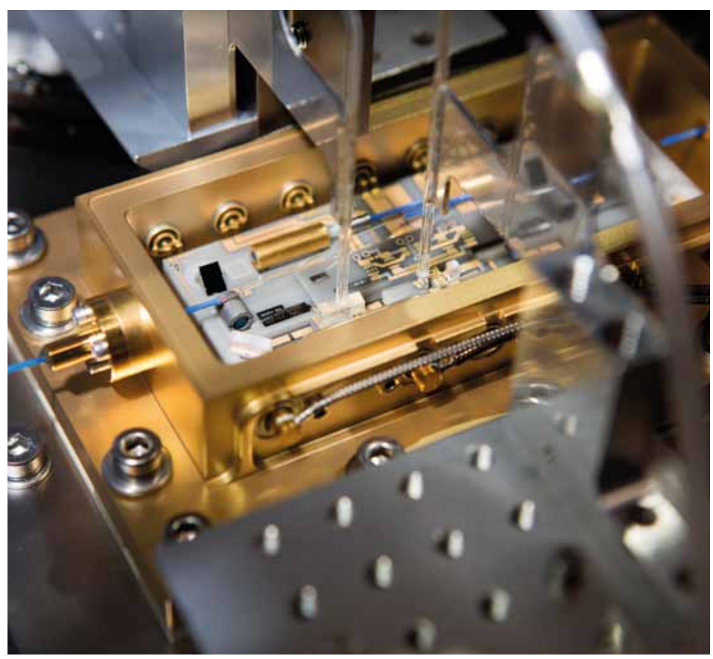
In our current frequent issue, we have compiled FBH developments used in space, which are, at the same time, technology drivers for a whole range of terrestrial applications. I wish you an inspiring reading!

Yours sincerely,
Günther Tränkle

Advanced micro-integration techniques

FBH has comprehensive experience in merging inherently energy-efficient diode lasers with advanced micro-integration techniques optimized to fit the respective application – including operation in harsh environments like space. High performance within a minimal footprint requires high integration density. For the optics, for instance, this implies using lenses with very small focal lengths, usually from a few 100 µm to a few mm. Efficient beam shaping, beam steering, and coupling into waveguides with typical dimensions of some µm can then only be achieved by very tight positional tolerances on the optics, in some cases well below 100 nm.

For deployment in space, it is required that integrated optics keep their precise alignment after facing vibrations, shocks or rapid thermal variations. Stability of components and processes is therefore comprehensively tested and validated during all development stages. One of the most sensitive functionalities in this context is on-board single-mode, polarization-maintaining fiber coupling with high efficiency (> 70 % coupling efficiency at power levels > 600 mW). The concept relies on very fine control of the angular alignment (< 0.001°) of the divergent output beam from a diode laser or an amplifier, first collimated via micro-optics and subsequently coupled into a fiber coupler via micro mirrors.

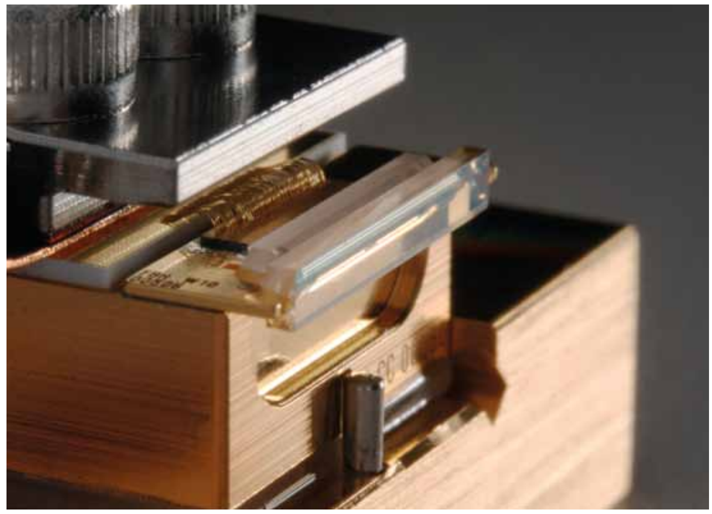


High-precision mounting of a fiber-coupled space-compatible diode laser module

The on-board fiber-coupling concept was tested sequentially against random vibrations at 8 g_{RMS} and 30 g_{RMS}, shocks of up to 1500 g, and 100 thermal cycles between -55°C and +70°C. Within measurement uncertainty, no loss of fiber-coupling efficiency was observed. This concept has been successfully implemented in FBH's micro-integrated laser modules for space applications.

Data highway in space – ultrafast optical communication at highest data rates

For more than 20 years, the Ferdinand-Braun-Institut has been closely cooperating with Tesat-Spacecom, the world's leading company in the field of optical satellite communication. Tesat supplies laser communication terminals (LCT) on behalf of the German Aerospace Center (DLR) as core components of the European Data Relay System (EDRS). This space data highway uses optical links to transfer information with highest data rates between low-orbiting and geostationary satellites. The latest LCT generation enables a data transmission rate in space of several Gbit/s over long distances up to 80,000 km. Based on the principle of coherent bidirectional transmission, the LCT is equipped with two frequency-stabilized Nd:YAG solid-state lasers, namely a transmitter and a local oscillator acting as demodulator to detect the received messages. These Nd:YAG lasers are pumped with FBH's semiconductor laser modules that offer high frequency stability, low intensity noise, and a long operating life under continuous temperature cycling and extraterrestrial irradiation.



FBH's high-power diode laser bar with optical elements used as pump source in laser communication terminals

FBH's laser diode benches – a power boost for laser communication

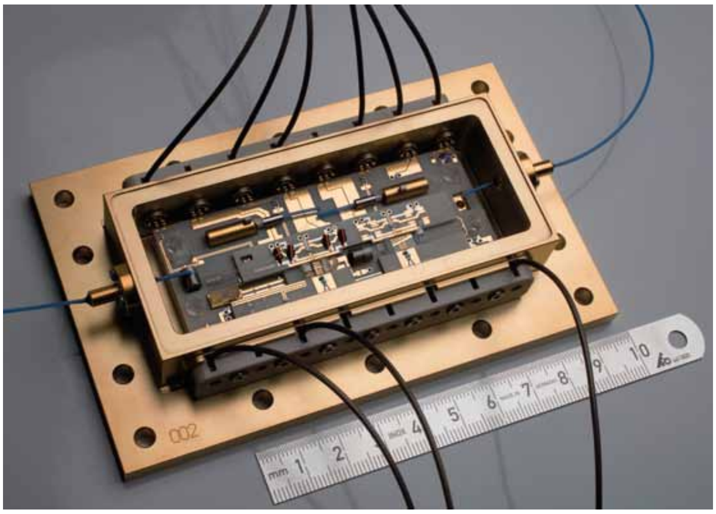
FBH has developed and qualified its laser diode benches (LDB) according to the standards of the European Space Agency (ESA) for space applications. The devices are designed to meet the extreme requirements of the LCT. The wavelength of the laser beam is stabilized to the pump transition band of the Nd:YAG (808 nm) while preventing the laser intensity to fluctuate in time, thus ensuring stable LCT performance. Furthermore, the diode laser must continuously operate over the mission's lifetime of 15 years with proven reliability (99.9 % on system level). This goal is achieved by a dedicated design keeping the power density small and including non-operating spare parts. Recent research efforts at FBH focus on novel concepts for on-chip integration of a sophisticated wavelength stabilizer, yielding both low noise and high reliability.

Laser communication terminal (LCT) integration and testing in Tesat-Spacecom's cleanroom

Reliable data transmission in space

Coherent transmission of data using LDBs from FBH was first demonstrated in 2008 between the satellites TerraSAR-X and NFIRE with an unprecedented rate of up to 5.6 Gbit/s over 5,000 km and from satellite to earth. Subsequently, the institute's devices were used in all further communication links established within EDRS. The focus was on low earth orbit (LEO) communication, but has been successfully tested also for the geostationary orbit (GEO) with Alphasat I-XL. In 2016, the first satellite of EDRS-A was launched into GEO, receiving images from earth through LCT transmission collected by Sentinel 1A on LEO to be then transmitted to the ground station without significant time delay. By 2021, three EDRS satellites placed in GEO shall be continuously accessible from almost every LEO position. This way, an optical network consisting of laser beams through space and relay satellites as switching nodes will be realized, thus opening a new dimension for the future of optical communications.

Laser systems for spaceborne quantum optical metrology



Micro-integrated ECDL-MOPA to be used for precision iodine spectroscopy in the JOKARUS experiment

FBH develops particularly compact and stable laser systems for harsh environments. Since 2008, the institute closely cooperates with Humboldt-Universität zu Berlin within its Joint Lab Laser Metrology, developing the laser systems required for QUANTUS (quantum gases in microgravity). The DLR-funded project investigates fundamental laws of physics with cold atoms as microscopic test masses under microgravity conditions performed in a drop tower and on board sounding rockets.

Meanwhile, laser systems developed by the Joint Lab Laser Metrology have been successfully applied in three sounding rocket missions, thus demonstrating their outstanding performance and reliability. In January 2017, as part of the MAIUS mission, a Bose–Einstein condensate (BEC) was created for the first time in space. In April 2015 and in January 2016, technological components of the MAIUS mission were successfully tested in the experiments FOKUS and KALEXUS.

Such experiments are innovation drivers for a wide range of applications, from GPS-free navigation to spaceborne geodesy. Moreover, with the advent of the "second quantum revolution", it is highly attractive to bring such technologies to market. The Joint Lab Laser Metrology has already taken up the challenge of developing laser systems for future portable quantum-technology-based devices.

Flexible technology platform for long-term space missions

The laser system of MAIUS was developed to perform laser cooling and atomic interferometry with ultra-cold rubidium atoms on a sounding rocket platform. It is based on a master oscillator power amplifier (MOPA) architecture with a DFB laser (MO) delivering narrow-linewidth (~ 1 MHz) laser light with low optical power and a tapered amplifier (PA) that ramps up the MO power up to some watts without degradation of linewidth. The MOPA is implemented on a ceramic substrate via hybrid micro-integration of laser chips, micro-optics, and discrete electronics.

The Joint Lab scientists have used their experience gained from the experiments with the MAIUS laser modules and applied this when developing the MiLas family of lasers. As a result, a laser technology for cold atom sensors on satellites is now available. Features include sealed housings, plugged electrical contacts, fiber-coupled inputs and outputs, and integrated thermal management. The concept of ECDL (extended cavity diode laser)-MOPA has been implemented for the first time within a single laser unit, achieving linewidths < 100 kHz with output powers ex single-mode, polarization-maintaining fiber > 500 mW.

MAIUS laser system developed by HU Berlin with integrated DFB-MOPA laser modules from the FBH used to successfully create a Bose-Einstein condensate for the first time in space

The first MiLas ECDL-MOPA emitting at a wavelength of 1064 nm has already been delivered and will be flown on a sounding rocket in the JOKARUS experiment, as part of an iodine-based frequency reference. The MAIUS-II experiment, with atom interferometry on species of rubidium and potassium on board a sounding rocket also implements ECDL-MOPA's emitting at 767 nm, 780 nm and 1064 nm. The next step is planned on the International Space Station (ISS), again with atom interferometry experiments. However, the MiLas laser modules also meet the requirements for a variety of alternative applications in space, for example coherent optical communications as well as for precision distance measurements. They are also designed to expand even deeper into space, be it in the context of "big-space" with high-performance spacecrafts or in the emerging context of "micro-space" on, for example, the CubeSat platform.

Energy-efficient electronics for satellites

Energy consumption and dissipated power are critical issues when operating microwave and mm-wave solid-state power amplifiers (SSPAs) in space, because the available DC power is limited and heat removal is hindered. However, conventional power amplifiers achieve the highest efficiency in the saturation region, where linearity is reduced. FBH is addressing this contradictory problem with two alternative solutions. In addition, FBH is working on GaN-based solutions for phased array systems for satellite communications at Ku-Band.

Envelope tracking based on a reverse buck converter

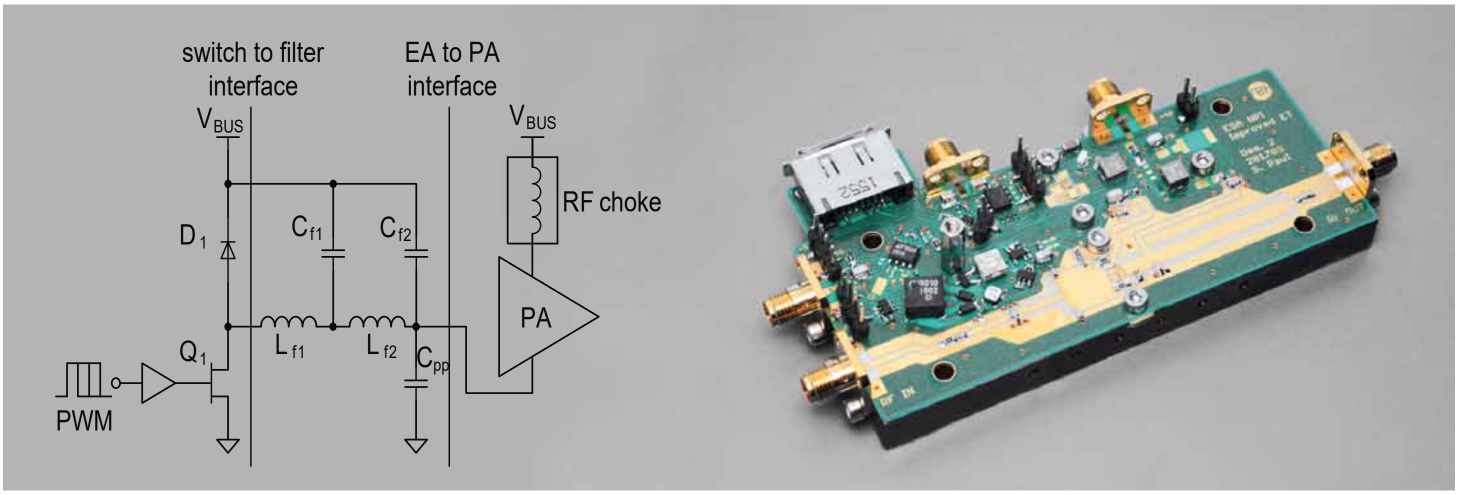
A well-proven efficiency enhancement technique is envelope tracking (ET), which modulates the supply voltage of the RF power amplifier (PA) in accordance to the instantaneous signal envelope. In a project financed by the European Space Agency (ESA) FBH develops such a system with the envelope amplifier (EA) in a reverse buck converter topology. The gate-source control of the final-stage transistor in the EA is operating with the source grounded. Thus, the load, i.e., the RF PA, is operating with a floating ground. Unlike in conventional buck converters, there is no need for an isolated gate driver in the EA. As a consequence, it features lower switching propagation delay enabling improved closed-loop control bandwidth. The proof-of-concept demonstrator operates at 1620 MHz and 40 V supply and shows 39 % overall power-added efficiency (PAE) at an average output power of 14.6 W for an 8 MHz modulated signal with 8.6 dB peak-to-average power ratio (PAPR). The reverse buck converter switches at 45 MHz with a PAE of 80 – 91 % for 16 – 40 V supply voltages. For the first time, a reverse buck topology system enabling GaN switching operation referred to ground has been shown in dynamic operation.

Advanced K-band power amplifiers with discrete supply modulation

Another promising concept for space applications in the K-band evaluated at FBH is the class-G topology or discrete supply modulation. Here, the supply voltage is modified in discrete steps according to the instantaneous signal envelope. A first quasi-static evaluation, applying this concept to the 0.15 µm FBH GaN-HEMT technology, shows a possible efficiency improvement of 13 %-points using a 2-level supply modulation at 20 GHz, operating with a 9 dB PAPR signal. Furthermore, the dissipated power can be reduced to 1/3 compared to fixed supply-voltage operation. This enables alternative architectures with reduced cooling effort, smaller footprint, and less weight. At present, the first integrated MMIC designs are being fabricated and novel approaches for digital isolation are being evaluated.

GaN technology for beam steering antennas and phased array systems

Realizing very efficient microwave power amplifiers enables powerful decentralized communication and radar systems where the broadcasted power is superimposed in the far-field of a multitude of antennas grouped in a linear or 2-dimensional array. Such arrangements are suitable for beam steering antenna and phased array systems. Among others, this technique is used in low-altitude earth orbiting satellites to track different ground stations and users electronically without any movable mechanical antenna parts. In a European project, FBH has developed the GaN chip technology for such a spaceborne system. Uplink power amplifiers at Ku-band delivering 13 W output power at 18 GHz with a PAE of 46 %, and low-noise receivers at Ka-band (30 GHz) with a noise figure of 2.7 dB have been demonstrated and delivered to partners for antenna array integration.



Simplified schematic (left) and photo (right) of the reverse buck converter

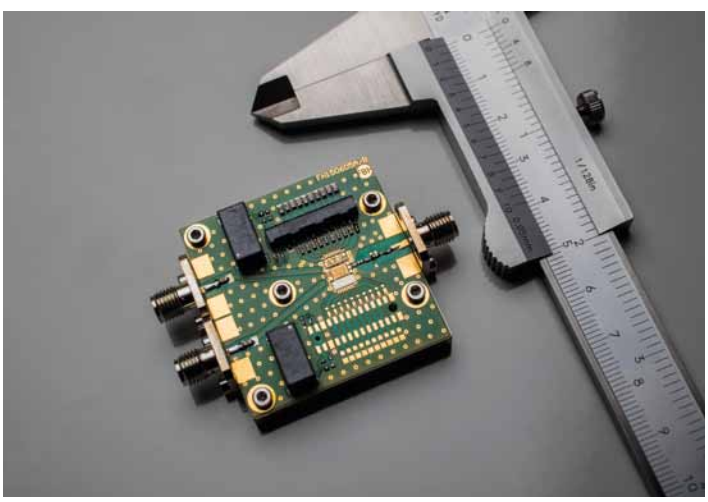
FBH lasers for investigations of climate-relevant atmospheric methane

The FBH has developed tailored laser diode benches based on FBH's proprietary QCW laser bars for pumping an ultra-precise LiDAR system to be launched into orbit in the time frame 2022/2023, as part of the French-German space cooperation, MERLIN. The Fraunhofer ILT in Aachen, Germany is responsible for the Laser-Opto-Mechanical-Assembly of the laser transmitter that generates high-power single-frequency pulses which are spectrally matched to a methane absorption line. The MERLIN satellite mission will advance climate and environmental investigations by measuring methane concentrations in the Earth's atmosphere with optical pulses, characterizing natural and anthropogenic sources of the gas. Methane is one of the most detrimental greenhouse gases.

FBH demonstrates fully digital transmitter chain

In common transmitter systems the baseband signal is usually generated in the digital domain, utilizing powerful but yet low-cost digital signal processors. However, upconversion and amplification are carried out in the analog domain. Recently, a fully digital transmitter chain was demonstrated at FBH, combining modulator and amplifier into one coherent system. This achievement is an important step towards the usability of such systems in real-world applications. Using a realistic test signal, the overall system performance could meet high standards regarding signal quality and linearity.

The system is designed as a drop-in replacement for present analog transmitter chains so that existing applications can be easily converted without requiring changes on the receiving side. The switch-mode amplifier MMIC fabricated uses FBH's GaN-HEMT process. While a traditional Tx chain has to utilize a power-hungry digital predistortion



Digital power amplifier module

to correct non-idealities of the amplifiers, FBH's digital PA modulator already incorporates provisions to eliminate them without any additional building blocks. Correction parameters can be estimated based on the system's live signal.

For demonstration purposes, up to 20 MHz WCDMA-like signals were used on a 900 MHz carrier. An ACLR of more than 52 dB in the neighboring channels was measured. Competitive efficiency results and linearity behavior were achieved. The system utilizes an easy-to-construct lumped LC filter as a bandpass with very low insertion loss while maintaining state-of-the-art linearity.

High-power Y-branch MOPA system with 9.7 nm combined wavelength tunability

High-power, diffraction-limited, and tunable narrow linewidth diode laser sources emitting in the near infrared are needed in applications like absorption spectroscopy, bio-medical imaging, and particularly for frequency conversion.

MOPA system in compact CCP package

FBH has recently developed a widely tunable, high-power light source, combining a tunable Y-branch distributed Bragg reflector diode laser (dual wavelength) master oscillator with a tapered amplifier into a hybrid master oscillator power amplifier (MOPA) system. The MO is collimated and coupled into the PA using cylindrical micro-lenses in a compact 25 mm × 25 mm conduction-cooled laser package.

The DBR gratings for the dual wavelength laser are designed for 973.67 nm and 975.91 nm, respectively. The emission width is smaller than 17 pm. Wavelength tuning of this device – 7.5 nm from each arm – is obtained by using an electrically controlled micro-heater, implemented on top of the grating sections of the MO. Together with the spectral distance of 2.23 nm between the two arms, wavelength tuning adds up to 9.7 nm. Results indicate that a total combined tunability of about 7.5 nm x N_{Arms} can be achieved. The PA ensures the amplification from both branches, with output powers of about 5.5 W. The emitted light features a propagation factor of M^2 = 2.2 along the slow axis, and a power content of 72 % within the central lobe (4 W diffraction-limited).

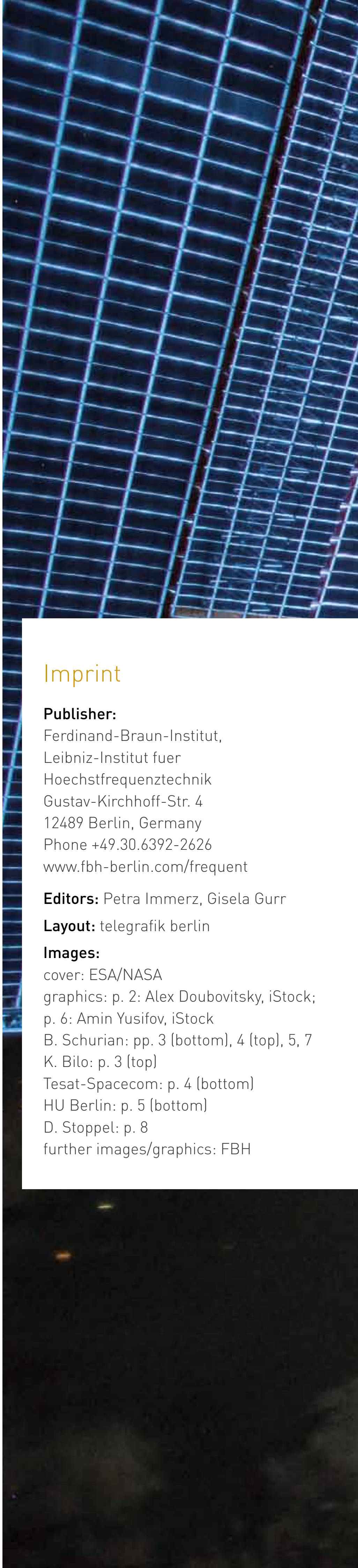
The Ferdinand-Braun-Institut, Leibniz-Institut fuer Hoechstfrequenztechnik (FBH) researches electronic and optical components, modules and systems based on compound semiconductors.

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 German technological excellence in microwave and optoelectronic research.

The Ferdinand-Braun-Institut develops high-value products and services for its partners in the research community and industry which are tailored precisely to fit individual needs. With its Prototype Engineering Lab, the institute additionally created an active interface between science and industry. By means of prototypes it turns excellent research results into market-oriented products, processes, and services. The institute thus offers its international customer base complete solutions and know-how as a one-stop agency – from design to ready-to-use modules and prototypes.



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