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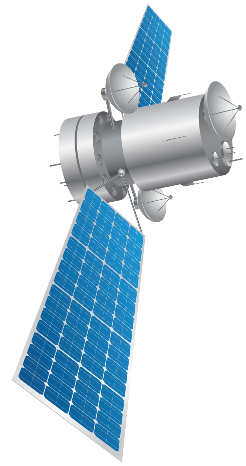
Institut

frequent

FBH developments for space

- application under challenging conditions
- spaceborne quantum optical metrology
- lasers for climate monitoring & ultrafast optical communication
- electronics for space

FBH developments for space – application under challenging conditions



The Ferdinand-Braun-Institut (FBH) has long-term and comprehensive experience in the development of III-V semiconductor-based components and sub-systems for applications in space. The institute has been working in projects with NASA, ESA, DLR and several companies in the space sector. A variety of R&D projects deal with spaceborne applications and technologies, including optical communications, quantum optical metrology, beam steering technologies, and energy-efficient electronics for satellites. FBH components developed for space are also technology drivers for terrestrial applications.

III-V technologies: an essential building-block for space equipment

Semiconductor technologies can be found in a multitude of space equipment, in laser instruments as well as in electronics for satellites. Thanks to their small form-factors, III-V semiconductor components can be built into very compact and robust packages. They are inherently energy-efficient and thus perfectly suited for deployment in space. In the last years, the rise in quantum technology-based experiments in space has sharply driven up the demand for diode laser-based payloads. Diode lasers provide the unique advantage of covering a very large wavelength range, approximately from 630 nm to 1180 nm in GaAs, and from the green spectral range down into the UV with GaN.

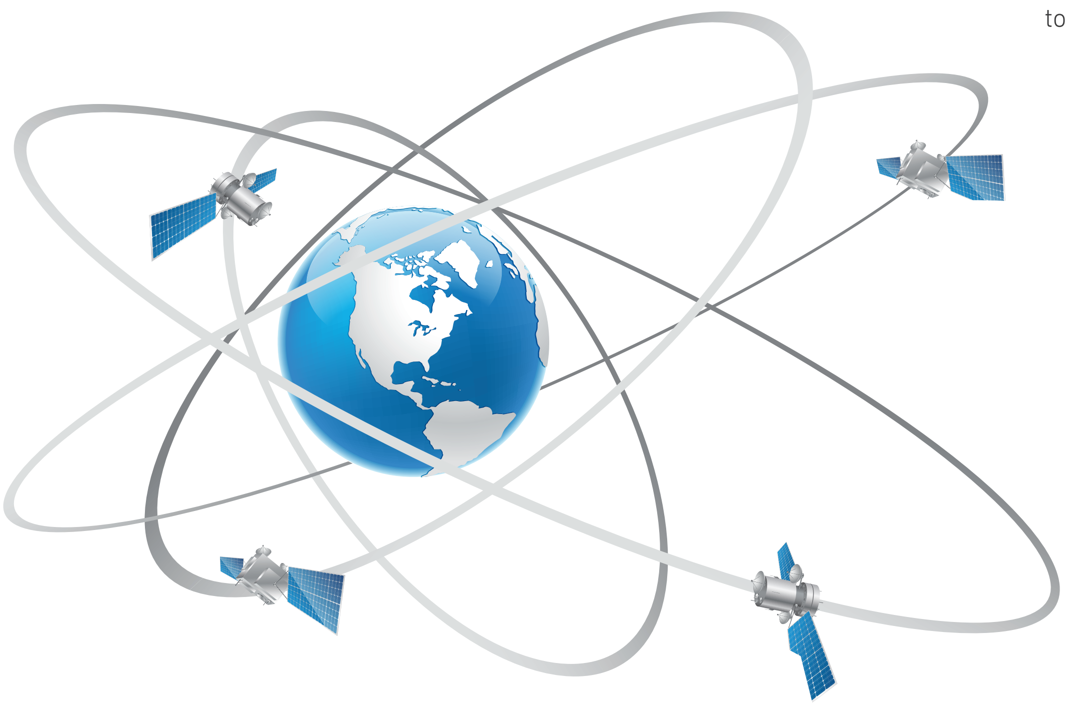
Heritage of space projects

Since almost two decades, we have been taking advantage of our unique know-how, carrying out projects with partners as well as directly delivering components and sub-systems for space flights. Through constant research, we have been able to improve the performance of our III-V semiconductor components and to offer higher functionality by micro-integrating the semiconductor chips into multi-functional modules. Since many years, we have been delivering GaAs-based diode laser pump modules for laser communication terminals and high-power, narrow-linewidth laser modules for quantum optical applications in microgravity. Moreover, research in collaboration with space agencies on GaN-based electronics for RF-power amplifiers, beam steering systems and phased-array radar systems is ongoing.

Space at FBH: the way forward

The volume of space-related projects at our institute has increased sharply in recent years due to the ever-increasing demand for modules and sub-systems with a multitude of integrated functionalities. Especially in institutional space missions with unique payloads, it is often extremely difficult to transfer the technologies developed to a commercial company in a timely manner. Owing to a lack of commercial alternatives, payload developers often require us to build at least the engineering and qualification models or even the flight models.

In the light of these demands, we plan to reinforce our commitment towards our partners in the space sector. In addition to our ongoing R&D in III-V semiconductors, we will therefore extend our capacities to cover sub-system development, small-series production and product assurance, thus enabling FBH to provide solutions along the development chain up to flight hardware.



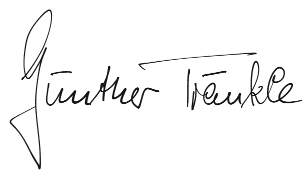
Editorial

FBH has a proven track record in supplying industrial and scientific partners with customized solutions for space applications.
Developments include reliable pump laser sources and radiation hardened transistors for satellites as well as hybrid-integrated laser modules used for cold-atom experiments in space.

In addition, one main focus of our expanded R&D activities towards quantum technologies is on quantum sensing applications in space. In close cooperation with Humboldt-Universität zu Berlin, we are aiming to increase the technology readiness level of these technologies up to deployment in space. We are thus paving the way for the enabling technologies of the future applications of quantum technologies.

In our current frequent issue, we have compiled the current state of FBH developments in these exciting fields. I wish you an inspiring reading,

Yours sincerely,
Günther Tränkle

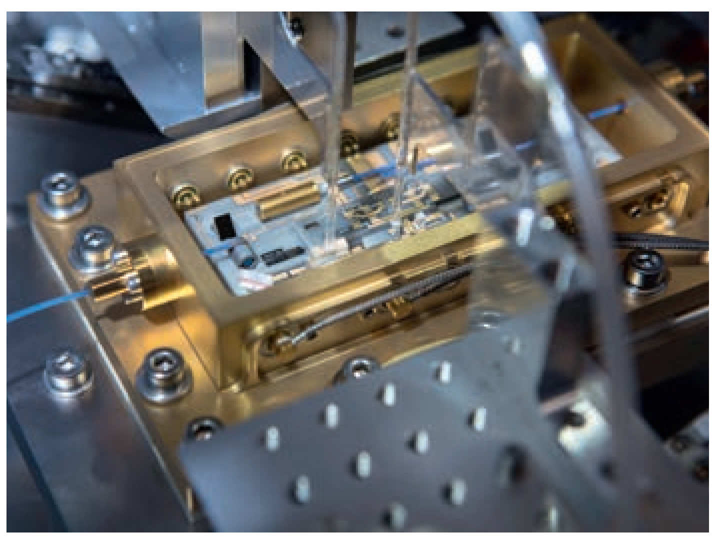


Advanced micro-integration techniques

We have 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.

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.



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

Spaceborne quantum optical metrology – from laser systems to atomic clocks and sensors

We apply our unique know-how in semiconductor laser technology and hybrid micro-integration techniques to develop particularly compact and stable laser systems for atomic sensors and clocks operating in harsh environments. Development of components, sub-systems and systems for space applications is supported consistently by product assurance, reliability tests and qualification programs for the respective mission scenarios.

Within the BMWi/DLR-funded program QUANTUS (quantum gases in microgravity), we have developed successive generations of laser systems in close cooperation with Humboldt-Universität zu Berlin (HU Berlin). The experiments carried out in a drop tower and on board of sounding rockets have yielded several milestones in the field, most notably the MAIUS experiment on a sounding rocket in 2017, realizing the first Bose-Einstein-Condensate (BEC) and fundamental atom interferometry studies in space. The next campaign, MAIUS-II, with dual-species rubidium and potassium BEC generation and atom interferometry on board a sounding rocket is scheduled for 2022.

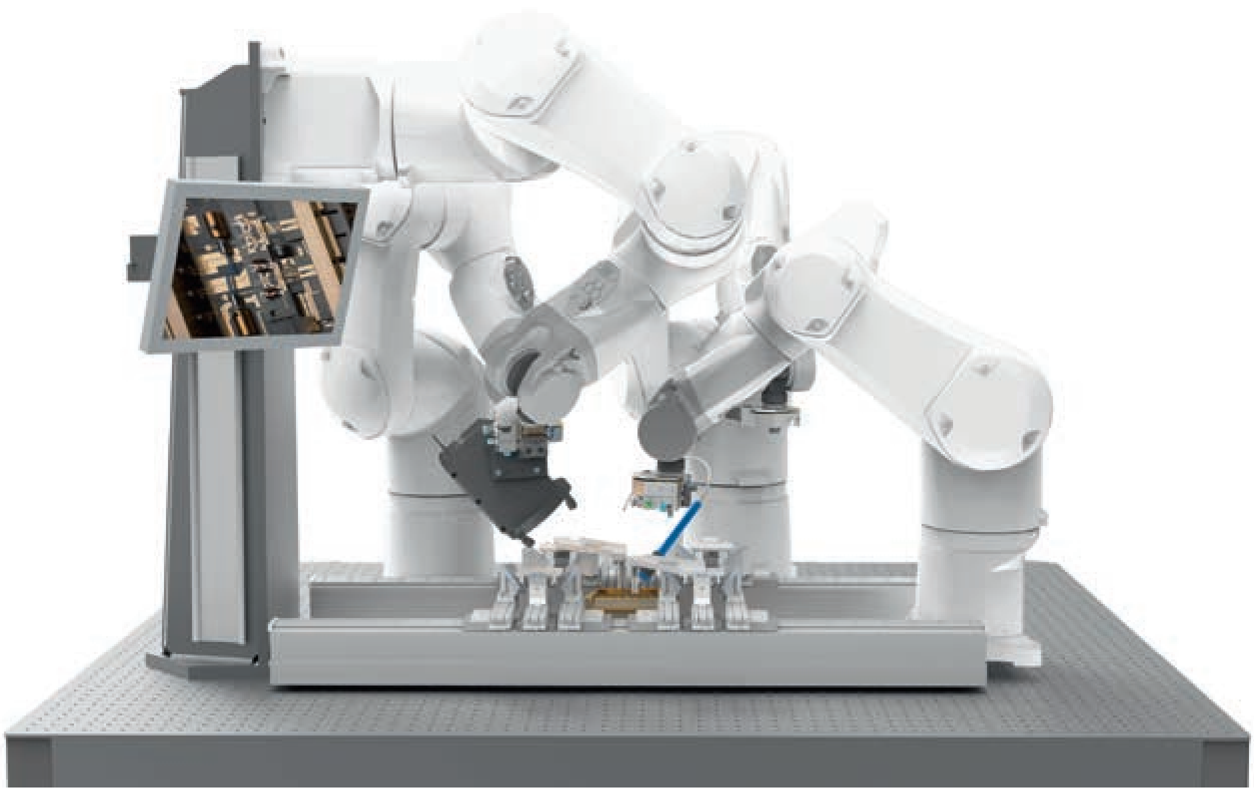
Based on the technological expertise accumulated by the QUANTUS/MAIUS team and NASA's Cold Atom Laboratory (CAL), the Bose-Einstein-Condensate Cold Atom Laboratory (BECCAL) is currently being built for operation on the International Space Station (ISS). The facility is jointly operated by NASA and DLR for experiments with cold atoms in the microgravity environment of the ISS. We have been contracted to deliver all laser modules needed to integrate three complete laser systems for BECCAL. Further laser modules of the same type are currently planned for cold atom experiments on an Einstein elevator and for an iodine-based atomic clock experiment on the ISS.

A viable technological platform for lasers in space

All laser systems for these experiments are based on high-power, narrow-linewidth lasers emitting at the wavelengths of 767 nm, 780 nm and 1064 nm. They are built on the same generic platform, namely the MiLas laser modules developed at FBH. The fully packaged modules with plug & play electrical and optical interfaces are easy to integrate into laser systems. Moreover, they are compact, lightweight, robust and energy-efficient – characteristics that make them a perfect solution for deployment in space, which can also be manufactured in high volumes.

Targeting future applications

We are additionally focusing on R&D activities which target future trends in spaceborne quantum optical metrology. The activities range from specific components, such as diode laser chips and micro-optical isolators, up to the micro-integration of complete atom-based systems for timing, field sensing and communication, the latter developed jointly with HU Berlin.



CAD view of a telerobotic assembly station currently under joint development by FBH and Robo Technology (© Robo Technology GmbH).

Compact optical frequency reference uniting a narrow-linewidth DFB laser diode with an integrated spectroscopy system suited for cold-atom quantum sensors and atomic clocks, including electronics and software for autonomous operation.

One of these future-oriented projects is CRONOS, where we are developing an engineering model of a micro-integrated optical frequency reference. The system is based on two-photon frequency modulation spectroscopy of atomic rubidium in a heated vapor cell with a narrowband diode laser system emitting at 778 nm. The optical frequency of the laser is stabilized to the spectrum of a narrow optical transition by an electronic control loop, representing a highly stable oscillator with a targeted relative frequency stability of $10^{-13} / \sqrt{\tau}$ at 385 THz. Supported with funds provided by BMWi/DLR, this project paves the way towards a compact, autonomous payload for a future in-orbit demonstration with performance relevant to global navigation satellite systems.

Within several projects, we are also developing core technologies for the future micro-integration of strontium-based optical frequency references. They either rely on Ramsey-Bordé interferometry of a thermal beam or precision spectroscopy of laser cooled atoms in an optical lattice. However, the technology readiness level for space application of such systems is still very low. We are also developing the red and blue-emitting diode laser chips required for laser cooling and the coherent manipulation of strontium atoms and study vacuum technologies to create a compact source and trapping cells.

Another R&D focus is on quantum memories. Only recently it has been theoretically shown that they could enable truly global quantum networking when deployed in space, thereby surpassing the limited range of land-based quantum repeaters. In space, they could also allow for novel protocols and long-range entanglement and teleportation applications suitable for deep-space links. Together with HU Berlin, we are enabling the experimental realization of atom-based memory modules in developing wafer level-based spectroscopy cells and micro-integrated memory modules, allowing for applications in space-based quantum networking

Outlook – where the path leads us

We focus on continuously developing and advancing the core technologies for spaceborne quantum optical metrology, acting as enablers for compact components, sub-systems and systems. Constant progress is achieved through the ever-increasing monolithic integration of functionalities into the semiconductor chip and miniaturization of packages. To reduce production time and costs, we have also started research programs aiming at artificial intelligence-supported automation and robotics for the microintegration of laser and photonic modules. Moreover, we develop additive manufacturing processes that enable realizing components with complex geometries and structures that cannot be manufactured using conventional methods. Processes for metallic and/or ceramic components in combination with selective metallization are particularly suitable for spaceborne quantum technologies. This approach can be used for rapid prototyping as well as for the development of different components of the physics packages (e.g., compact vacuum chambers, atomic oven and sources, RF antennas).

Advantages at a glance

- **one stop-shop** – from semiconductor chip design to delivery of fully-packaged modules
  - unique diode lasers & modules with proven reliability (incl. facet passivation based on vacuum cleaving)
  - expertise on GaN MMICs for beam steering transmit / receive modules & GaN power electronics for space
- **product assurance along the value chain:** performance & reliability testing plus qualification for space
- **small-series production capabilities** in ISO4-class laboratories, up to flight hardware
- **system-level integration** of devices for timing, field sensing and communications

Climate monitoring via satellite – tracking down the sources of methane

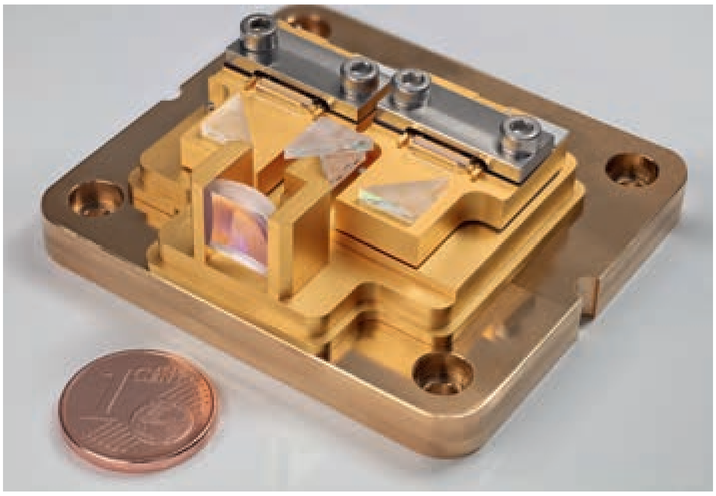
Merlin climate satellite – to monitor the greenhouse gas methane (© ESA).

Merlin, the methane remote sensing LiDAR mission, is a French-German satellite project scheduled to be launched in 2025 to measure the global distribution of methane. Although this greenhouse gas is much less concentrated in the air than carbon dioxide, its global warming potential is much higher. Investigating its sources is therefore crucial to better tackle these climate-damaging emissions in the future.

We developed, qualified and delivered laser modules for this mission. Each of them is equipped with two high-power laser half-bars, providing 130 W pulsed emission at 808 nm wavelength. The modules are pumping a Nd:YAG laser inside an optical parametric oscillator (OPO) provided by Fraunhofer ILT. The OPO serves as the light source of an Integrated Path Differential Absorption LiDAR, measuring the local concentration of methane in the atmosphere by emitting and detecting short laser pulses around the absorption line of the gas. Our pump lasers were qualified by in-house overstressed life tests of 320 single emitters with 4.8 billion shots per laser half-bar, resulting in 99.99 % reliability over five years of operation at 99 % confidence level. The operational endurance over the full mission load was independently confirmed by ESA's technology center ESTEC.

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

For more than 20 years, we have been closely cooperating with Tesat-Spacecom, the world's leading company in the field of optical satellite communications. 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 45,000 km. Each LCT is equipped with two frequency-stabilized Nd:YAG solid-state lasers, pumped by FBH's semiconductor lasers. These modules offer high frequency stability, low intensity noise, and a long operating life under continuous temperature cycling and extraterrestrial irradiation. We are also pursuing R&D activities towards the realization of all-diode laser-based solutions for coherent intersatellite communication.



DBR laser array module for future space missions – designed for over 15 years of reliable and superior low-noise operation in space.

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

We have developed and qualified our 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 a Nd:YAG laser (808 nm) while preventing the laser radiation to fluctuate in time, thus ensuring stable LCT performance. Furthermore, the diode lasers must continuously operate over the mission's lifetime of 15 years with proven reliability (99.9 % on system level). We achieve this goal by a dedicated design that keeps the power density small and by including non-operating spare parts. Research efforts at FBH have also been focused on integrating a wavelength-stabilizing Bragg reflector on chip level, yielding both low noise and high reliability. Extended life test campaigns have been performed to prove that the DBR laser array modules are suited for over 15 years of continuous operation. This is the precondition for qualifying these lasers as flight hardware for the next LCT space missions.

Electronics for space

Efficient radiation hardened electronics for spaceborne energy converters

All electric users in a spacecraft or satellite rely on efficient conversion of the electricity generated in the solar panels. This requires radiation hardened power converters. We have developed normally-off GaN power switching transistors to operate power conversion systems up to 650 V drain bias. The institute has also considerable experience in space-related radiation testing, such as exposure to gamma rays (total dose tests, TID), single event tests using heavy ions (SEE), and neutron irradiation tests. Thus, an ambient knowledge on radiation sensitivity of GaN power switching devices is available that can be utilized to specifically develop radiation hardened power switching devices.

First GaN microwave devices deployed on a European geostationary satellite

For more than 20 years, we have been systematically developing discrete and monolithically integrated GaN-based microwave devices for applications from L- to Ka-band. Within an ESA-funded project, we supplied dedicated discrete GaN chips for a payload experiment to be flown on the Alphasat satellite. These FBH GaN chips operate in a 2.5 GHz oscillator and are subjected to the radiation present in the geostationary orbit. Alphasat was launched in 2013, and since then the GaN oscillators are monitored regularly, thus demonstrating that they run without major degradation.

Highly efficient transmitters for Ka-band beam steering applications

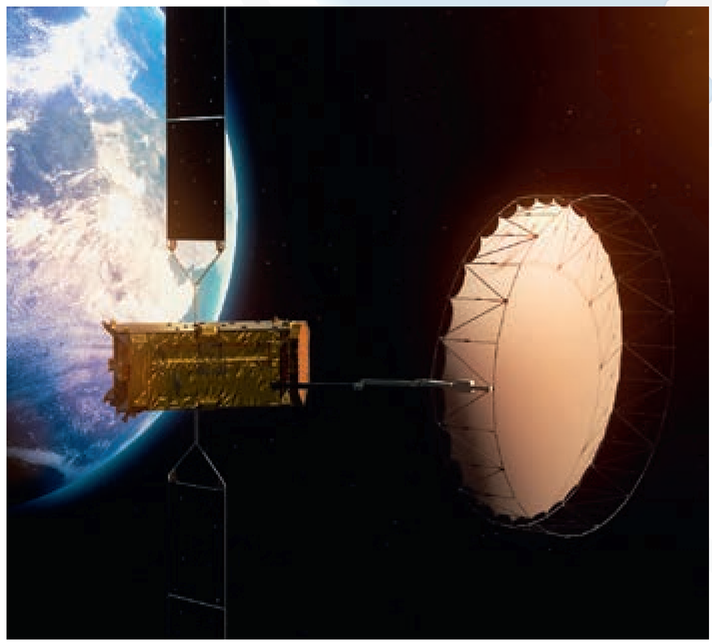
In 2021, the Kassiopeia project led by FBH was launched to demonstrate a fully independent supply chain based on Europe's internationally leading technologies, from SiC substrates, GaN epitaxy, GaN device processing up to power amplifier modules for Ka-band spaceborne beam steering applications. For this purpose, Ka-band MMICs using novel epitaxy, processing, and circuit concepts towards highly efficient GaN and AlN devices will be developed and demonstrated. The goal is to substantially increase the efficiency of GaN technology at Ka-band, making it even more attractive for space applications.

MIMO imaging radar for space rendezvous and deorbiting

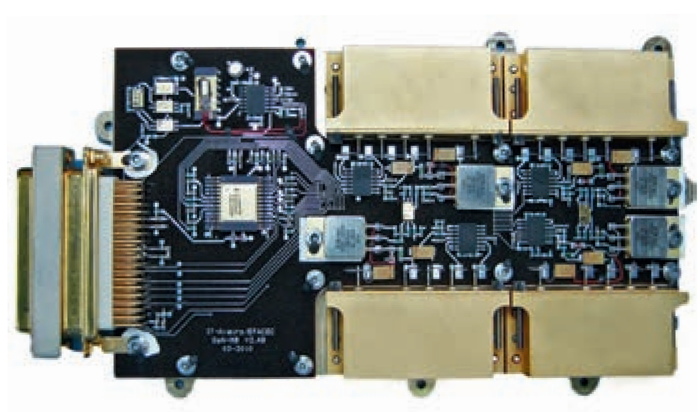
We are also developing technologies for a MIMO modular and compact imaging radar based on European technologies. The radar is designed for W-band operation 85 – 95 GHz using dedicated front-end components. These include a microwave direct digital synthesis in SiGe technology and compact MMIC up- and down-converters with integrated amplifiers, realized with in-house FBH InP DHBT technology. All components are assembled with the newly developed FBH interconnect technology on a single dedicated PCB in a tile configuration. The tiles will comprise self-sustained imaging modules, which can be placed anywhere on the satellite.

Terahertz imaging sensors, focal-plane arrays, and cameras

For about 10 years, we have been developing THz imaging sensors using its GaN MMIC process – robust high sensitivity and low-noise THz detectors based on FET devices. These detector devices can be realized both as focal-plane arrays and THz cameras in the frequency range 0.1 – 6 THz with instantaneous bandwidths exceeding 1.5 THz. They exhibit integrated antenna structures based on a proprietary GaN design and process. Supplemented with read-out electronics, they have been deployed in various scenarios including passive and spectroscopic imaging. The present THz camera with an operational bandwidth of 0.1 – 2 THz and monolithically integrated 12 x 12 pixels can be stitched to even larger arrays, offering low-noise performance of individual pixels.



FBH's GaN chips are still working flawlessly on the Alphasat satellite, launched in July 2013 (© ESA).



Final Alphasat flight demonstrator containing 4 GaN oscillator modules. (© Uni Aveiro/Efacec, Portugal)

The Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenz-technik (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 and integrated quantum technology. 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 energy-efficient low-voltage drivers for use in a variety of applications.

The FBH is a center of competence 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. Within Research Fab Microelectronics Germany (Forschungsfabrik Mikroelektronik Deutschland), it joins forces with 12 other German research institutes, thus offering the complete micro and nanoelectronics value chain as a one-stop-shop.

In close cooperation with industry, FBH's research results lead to cutting-edge products. The institute also successfully turns innovative product ideas into spin-off companies. With its Prototype Engineering Lab, the institute strengthens its cooperation with customers in industry by turning excellent research results into market-oriented products, processes, and services.

The institute offers its international customer base complete solutions and know-how as a one-stop agency – from design to ready-to-use modules and prototypes. Overall, working in strategic partnerships with industry, FBH ensures Germany's technological excellence in microwave and optoelectronic research.

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