Leibniz
Ferdinand
Braun
Institut

frequent

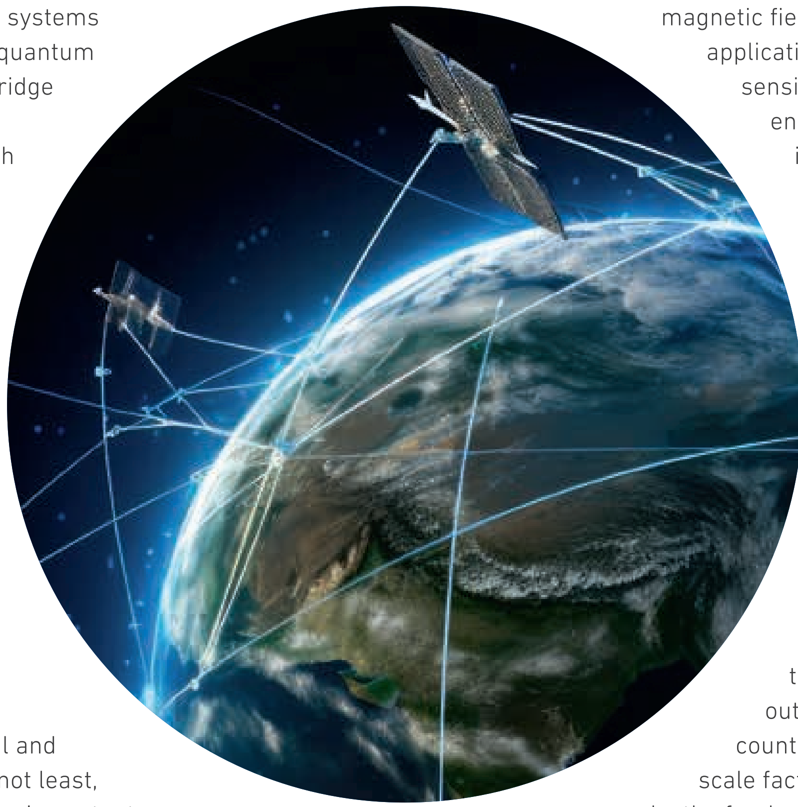
FBH developments for quantum technology applications

- enabling exceptional capabilities
- optical atomic clocks
- magnetometers & quantum-enhanced imaging
- quantum computing & information processing
- quantum communication & quantum networking

Quantum technologies – enabling novel applications with exceptional capabilities

Quantum technologies exploit quantum physics to create novel solutions in various fields including computing, communications, and sensing. They are capable of both enhancing the performance of existing classical solutions and providing solutions to problems for which no established approaches yet exist.

At the Ferdinand-Braun-Institut (FBH), we perform the related R&D, ranging from key technologies to components and modules to systems that enable or even provide quantum solutions. We successfully bridge the gap between basic and application-oriented research by closely cooperating with Humboldt-Universität zu Berlin within four jointly operated labs. Two of which carry out R&D in quantum information technology while the other two focus on quantum sensing applications. These R&D activities aim at bringing quantum technology from proof-of-concept demonstrations in a lab to industry, which makes us an integral part in value chains of our industrial and scientific partners. Last but not least, quantum technologies play an important role for Germany as a high-tech nation, since they are expected to decisively shape the technological, economic, and social development of our society.



Quantum computers will solve problems that are not feasible with classical computers: They are, for example, expected to decrypt messages that are considered secure today – given existing and near-future classical computers. Therefore, we do not only develop solutions for **quantum computers** and **quantum networks** but we are also addressing **quantum communication.** Our multifaceted developments for quantum information technology include entangled photon sources based on spontaneous parametric down conversion in crystals or semiconductors as well as single photon sources based on color centers in various material systems, such as diamond and silicon carbide. To realize quantum memories, we pursue different approaches based on color centers and room-temperature atomic vapor cells. We also provide compact and robust high-power, narrow and ultra-narrow linewidth lasers as well as light control units for neutral-atom and ion-based quantum computers and quantum network applications.

Quantum sensing causes a paradigm shift in various sensing application fields. These range from magnetic field detection for bio-physical applications and sub-wavelength sensing of electrical fields to enhanced imaging in the mid-infrared and inertial sensing for navigation up to accurate time keeping for navigation, data center synchronization, and fundamental physics. Last but not least, quantum sensors play a key role in realizing SI-units (SI – international system of units) for various physical quantities. They often surpass conventional devices in terms of sensitivity. With respect to accuracy, they always outperform their classical counterparts, since the sensor's scale factor is completely defined by the fundamental physical constants.

In addition to our particularly compact, robust laser modules and light control units, we also develop miniaturized and even chip-scale physics packages. For magnetometers and optical atomic clocks, we cover the whole value chain up to the complete system. We specifically develop optical clocks and laser modules for space applications that have already demonstrated their capability in the field.

» We successfully bridge the gap between basic and application-oriented research …

Interested?

Then please do get in touch with us!

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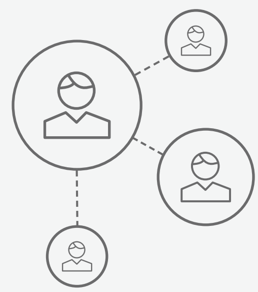
Benefits of a cooperation with FBH

+ **World-leading III-V technology** (laser diodes) and world-wide unique hybrid integration technology
+ **Internationally recognized high-performance** photonic components, modules, and systems
+ **Customization** according to our customers' needs
+ **Track record** of successful cooperation
+ **Broadly skilled** scientific team with decades of experience
+ **Comprehensive experience** with space projects and space-specific product assurance
+ **Comprehensive, application-specific expertise** through Joint Labs with Humboldt-Universität zu Berlin

Ways of cooperating with us

- **Joint research project**
- **Industrial contract**
- **Direct sales or licensing**
- **Cooperation within FMD-QNC**
  www.module-qnc.de



Competencies and capabilities in quantum technology R&D: from custom chips to leading-edge systems

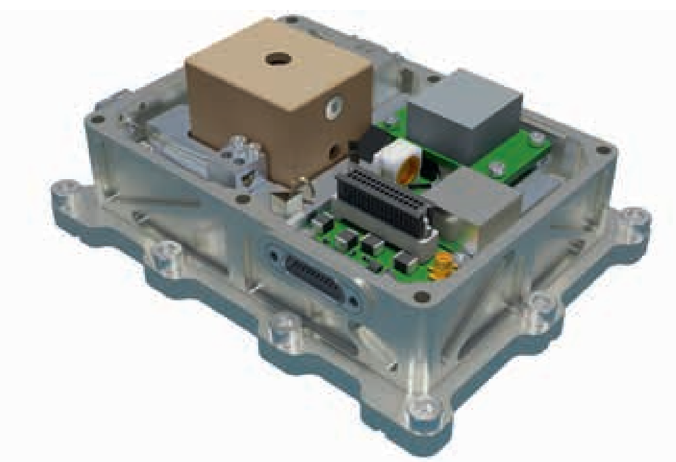
- GaAs (620 – 1180 nm) & GaN (~ 400 nm) diode laser development: from simulation & design to processing, assembly & characterization
- Diamond nanophotonic (spin) devices for quantum communication & information: from modelling & design to processing
- AlGaN integrated photonic circuits: passive photonic integrated components & electro-optically controlled photonic components
- Opto-electronic modules & atomic physics packages based on ultra-precise hybrid micro-integration technology
- System development: design, integration & testing
- Product assurance (specifically for space projects) incl reliability & environmental testing (from modules to complete science payloads)
- Cleanroom facilities (up to ISO 4) for assembly of critical photonic modules

Unlocking precision: mobile atomic clocks by FBH

Precise timing is key to many applications, ranging from data center synchronization to satellites in space that furnish timing signals for global navigation satellite systems (GNSS). At FBH, we are advancing the related optical frequency reference technologies to outperform conventional RF clocks in terms of accuracy and stability. Moreover, we are aiming to reduce their size, weight, and power (SWaP) budget, thus allowing for mobile applications, e.g. on satellites.

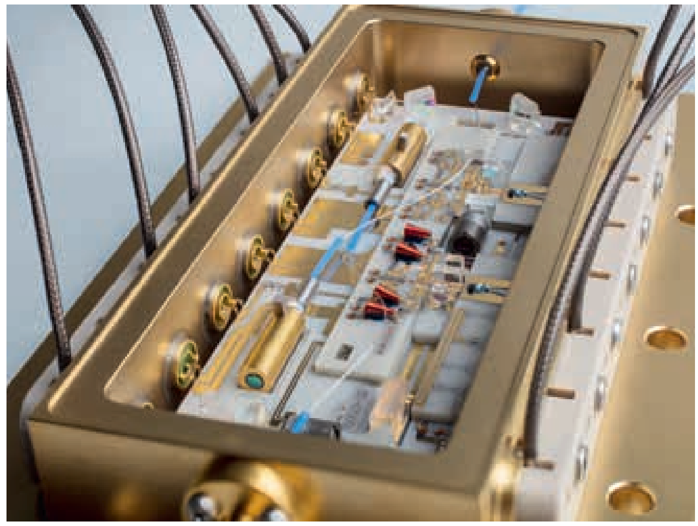
We provide the core competencies for satellite-based optical clocks by developing and fabricating stable, reliable, and miniaturized laser light generation and light control units as well as physics packages.

Our unique heritage in the development and fabrication of GaAs laser diodes (620 – 1180 nm) and distinctive hybrid micro-integration technology are key to realizing compact and robust opto-electronic modules. Miniaturization is accomplished using our ultrahigh-resolution robotic integration facility to realize laser modules, e.g., for a laser cooling application (medium linewidth) as well as for the interrogation of a clock transition (ultra-narrow linewidth). Further, light control units can be realized that properly superimpose, condition, and pulse the light provided by the lasers.



Rendering of the optical frequency reference based on the 2-photon clock transition of rubidium.

We plan, simulate, and produce compact physics packages as small as a palm of the hand, conditioning the laser beam for clock operation and providing long-term stability. Completed micro-assemblies of the physics packages are subsequently integrated into hermetically sealed housings and safeguarded from the surrounding environment. This allows to undisturbedly operate the laser frequency stabilization.



External cavity diode laser with semiconductor optical amplifier for an iodine-based, space-borne optical frequency reference.

We also develop various optical clocks and frequency references. One of those builds upon a narrow-linewidth two-photon transition in rubidium. This development is supported by a laboratory-based experiment, which shows state-of-the-art performance metrics data in terms of size and type of transition it employs. The comprehensive system is scheduled to be fully operational, rigorously tested, and primed for flight by the year 2026.

VCSEL for inertial satellite navigation

Quantum sensors enable navigation in areas where signals provided by GNSS like the European Galileo system are not available, e.g., on trains in tunnels, and on spacecrafts in deep space. We rely on our established GaAs diode laser technology to develop vertical cavity surface emitting lasers (VCSELs) operating near 795 nm. These are needed for a high-accuracy angular rate sensor that will be used to precisely control satellite pointing in future “new space”-based communication satellite systems.

Product assurance for space activities

FBH’s product assurance team accompanies projects, ensuring smooth delivery of reliable space hardware. The team oversees project management, procurement, qualification, and the manufacturing, assembly, integration, and testing (MAIT) activities.

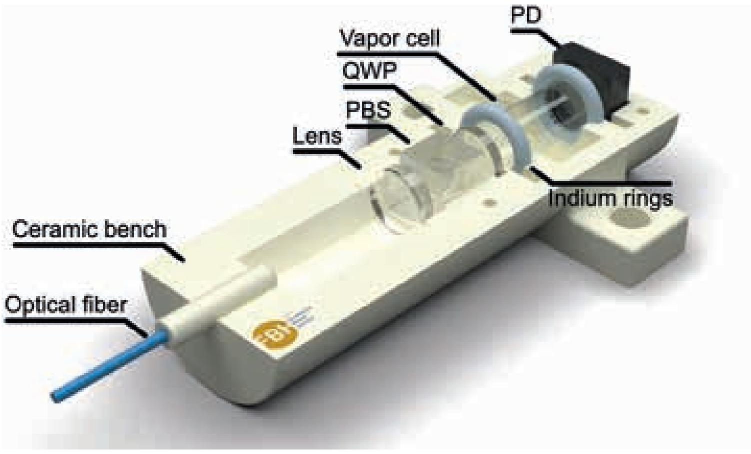
Magnetometers & quantum-enhanced imaging

Magnetometers for astro-medical applications

Optically pumped magnetometers (OPMs) are cutting-edge quantum sensors for magnetic field measurements. They attain high sensitivities to external magnetic fields by utilizing laser light-aligned spins in warm vapors, such as rubidium and cesium.

During extended space missions, it is crucial to monitor astronauts' neuromuscular condition, thus adapting their training. Magnetomyography with OPMs is a promising approach to go beyond classical surface electromyography to record functional processes in muscles with high temporal resolution.

At FBH, we develop a compact and robust OPM, aiming for sensitivities in the sub-pT range to achieve medical relevance. The physics package of the sensor head consists of a ceramic bench with optical components.



CAD drawing of the optically pumped magnetometer.

Magnetometers for material monitoring & medical applications

Robust solid-state-based OPMs based on nitrogen-vacancy color centers in diamond are an alternative to warm vapor sensors. Such sensors can even be operated in harsh environments and at almost any background magnetic field, making them applicable in mobile applications.

We develop infrared-absorption magnetometers using 1042 nm lasers that monitor the magnetic field-sensitive transmittivity and allow us to determine AC and DC magnetic fields. We already demonstrated 100 pT/sqrt(Hz) sensitivity and are aiming to reduce this value down to 1 pT/sqrt(Hz). Moreover, we are designing and building multipixel sensor units for the two-dimensional measurement of magnetic fields.

Heritage of R&D for quantum sensors – used for physics in space

We develop and deliver complex and robust laser modules – unrivaled in terms of SWaP budget and performance – for quantum sensors deployed on sounding rockets, the ISS, and on satellites. They facilitate quantum sensor applications in fundamental physics, geo- and environmental physics, and time keeping and navigation.

FBH's expertise in realizing highly specialized diode laser modules is the basis for novel quantum light modules.

FBH lasers powering a quantum imaging sensor system

Mid-infrared (mid-IR) light is commonly used to investigate microplastics in water, analyze tissue for cancer diagnostics, and for non-destructive testing of ceramic materials. Since handling mid-IR light is technically very demanding, quantum sensor technology relying on quantum light modules which use “undetected photons” opens up a straightforward approach.

For mid-IR hyperspectral imaging and quantum OCT (optical coherence tomography) sensing, we develop the required hybrid integrated, miniaturized quantum light modules. We integrate specially developed, novel laser diodes and micro-optical elements together with a nonlinear optical crystal into a very compact package. These modules create entangled photon pairs that interfere in a nonlinear interferometer, thus making the mid-IR spectral range accessible. Measurements are performed exclusively with high-resolution spectrometers in the near-infrared range so that neither detectors nor additional radiation sources in the mid-IR are required.

Pioneering advances in quantum computing & information processing

Quantum computing leverages quantum mechanics to process information quickly. Quantum bits (qubits) can exist in multiple states simultaneously and enable quantum computers, together with entanglement, to solve complex problems exponentially faster, impacting cryptography, optimization, and scientific simulations. Challenges include qubit stability and error management. Quantum computing promises revolutionary advancements, potentially transforming industries and unlocking new frontiers of computation.

Photonic quantum computing aims to utilize the distinct characteristics of light particles. At its core is a photonic processor used to measure photonic resource states. Generating such states is highly challenging. One promising scheme is to apply photonic cluster states, which reduces the complexity of implementing the quantum circuit measurement compared to superconducting quantum computers, for example.

We are developing the photonic integrated circuits needed to implement the required quantum operations and to generate the photonic cluster states. For the photonic platform, we are using AlGaN heterostructures to enable electro-optically controlled circuits suitable for fast and precise on-chip operations and measurements.

To realize computational resource states, we investigate the efficient generation of photonic cluster states with optically active spin defects in diamond. Such defects have the potential to enable complex resource states. We design and fabricate nanophotonic spin-photon interfaces in diamond, including a sawfish-like cavity that enables entangled photon generation with unprecedented efficiency.

We also develop unparalleled **laser modules and light control units** as enabling devices, for example, in neutral atom- and ion-based quantum computers and quantum network applications. Hybrid micro-integrated laser modules used for calcium-ion-based quantum network applications, for example, provide 400 mW of optical power at 794 nm with a 3 dB linewidth of 60 kHz (1 ms). Utilizing miniature electro- and acousto-optic modulators, we also realize distribution modules for quantum computing and quantum sensing.

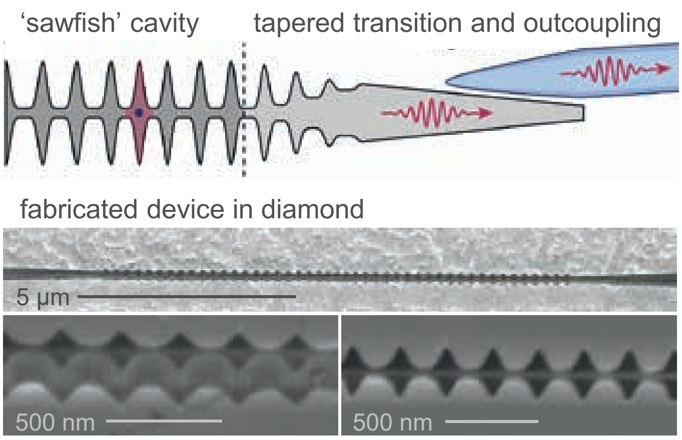
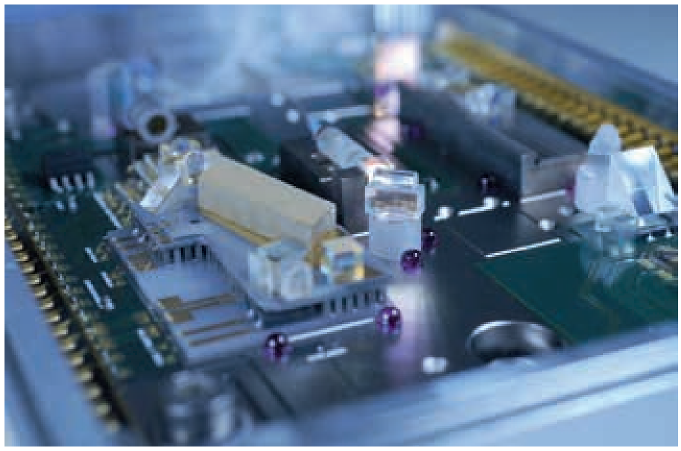


Illustration of a spin-photon interface for the efficient fiber coupling of photonic resource states. Bottom: Scanning electron micrographs of fabricated interfaces in diamond.



794 nm extended cavity diode laser module (139 x 80 x 33 mm³, 800 g) – the basis for a compact, reliable, and automated laser system for operation with calcium ions in quantum information technology.

Miniaturization & automation: hybrid micro-integration at FBH

Our unique and versatile hybrid micro-integration technology facilitates the assembly of highly complex, compact, and robust photonic modules. It allows to align and bond up to four miniature components simultaneously with sub-100 nm accuracy. Moreover, we are developing agile industry-compatible assembly stations that are optimized for low-volume production, combining various robots with an advanced control industry-5.0-based architecture.

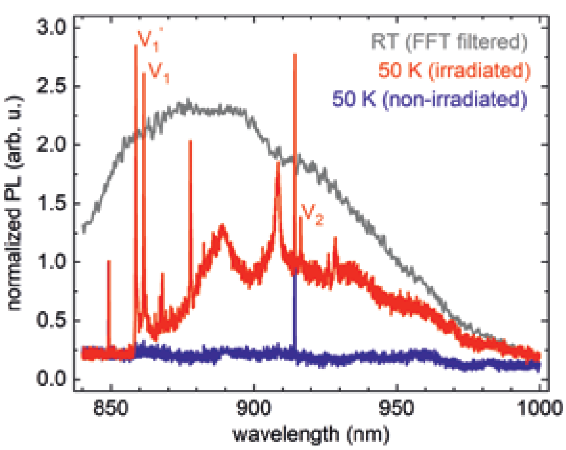
Secure quantum communication & quantum networking

Quantum communication and quantum networking leverage quantum mechanics for secure data exchange and interconnected quantum systems. Unbreakable encryption through protocols like quantum key distribution relies on **single photon quantum states**. Extended protocols are enabled by **entangled photon pairs**. Quantum networks are based on entanglement generation and require **quantum memories** to extend applications to distributed quantum computing and teleportation. For communication distances beyond roughly 100 km, **quantum repeaters** are required that overcome losses in optical fibers.

Single photon light sources

To generate single photon quantum states, one possible source are color centers, i.e. optically active defects in wide bandgap materials, which enable a compact and robust technologic integration. One promising type of defect are negatively charged silicon defects (V_{Si}) in silicon carbide (SiC), combining single photon emission at room temperature with a material platform of high technological maturity and suitable optical properties.

We create V_{Si} by bombardment of SiC with light helium ions in a helium ion microscope. Its beam focus of less than 1 nm allows to generate complex patterns with locally varying dose rates. We are currently developing the deterministic generation of such single quantum emitters.



Defect creation in 4H-SiC – fluorescence emission spectra (grey line) of charged Si defects (V_{Si}) in silicon carbide. The characteristic zero phonon lines are observed at low temperatures (red line) and appear only in the irradiated regions.

Quantum memories

Quantum memories are an integral part of quantum networks. Analog to computer memories, they can store a quantum state for later read-out. A variety of physical systems can be used to implement quantum memories. We investigate two fundamentally different types: atomic vapor-based memories and single spin-based memories in color centers. Atomic vapor-based memories have the advantage that many quantum states can be stored at the same time, while spins allow for relatively longer storage times.

Quantum repeater protocols & component development

Classical light-based communication over long distances relies on amplification in repeater stations. Quantum physics, however, requires quantum repeaters using entanglement. We are developing and realizing new concepts and components for quantum repeater architectures as backbone for future quantum networks. A very promising scheme are one-way quantum repeaters that rely on photonic cluster states. We have demonstrated theoretically that such repeaters can be built resource efficiently. For physical implementation, we fabricate nanophotonic spin-photon interfaces and operate these at temperatures of only a few Kelvin.

Quantum communication in space

We are currently contributing to the development of a compact single-photon source to enhance secure communication in satellite-based quantum key distribution (QKD). Our laser will excite a quantum light source based on a color center in hexagonal boron nitride. This system is part of a space-payload to be integrated into a 3U CubeSat, scheduled for launch into low Earth orbit in 2024.

The Ferdinand-Braun-Institut (FBH) is an application-oriented research institute in the fields of high-frequency electronics, photonics, and quantum physics. It 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 such as communications, energy, health, and mobility. Specifically, FBH develops light sources from the near-infrared 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 covering the full range of capabilities, from design through fabrication to device characterization. Within the Research Fab Microelectronics Germany (Forschungsfabrik Mikroelektronik Deutschland – FMD), FBH 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 and strategic partnership 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 thereby 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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