

Press Release

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Laser processes to enable robust, miniaturized beam sources for quantum technology

In the HiPEQ project, a consortium of industry and research partners has developed new laser-based approaches to enable miniaturized, robust beam sources for quantum technology. Among others, the consortium also used lasers to grow novel optical isolator crystals. Funded with 6.22 million euros by the German Federal Ministry of Research, Technology, and Space (BMFTR), the project achieved significant progress from November 2021 to July 2025. Fraunhofer ILT in Aachen played a key role by co-developing the laser processes needed.

Currently, beam sources for quantum technology applications are often complex, large, and not robust enough for field use. What is needed, then, are miniaturized systems that are as versatile as possible. The BMFTR-funded project "HiPEQ – Highly Integrated PIC-Based ECDLs for Quantum Technology" has developed such a beam source.

Coordinated by TOPTICA, later a systems integrator, a consortium of industry and research partners has built prototypes of two miniaturized laser sources. With external dimensions of just 22 x 9 x 6 cm³, they provide enough space for all system components. The design can also be adapted to other wavelengths, making them suitable for a wide range of quantum technology applications.

In this project, Fraunhofer ILT made a significant contribution to the successful growth of previously unattainable crystals for novel Faraday isolators. In a second work package, the Aachen-based team designed a glass packaging module with µm-precise mounts for fiber coupling and important system components.

Compact, rugged, and flexible

The laser systems are based on photonic integrated circuits (PICs), optical fibers, a fiber coupler, and an optical isolator that prevents reflected light from re-entering the laser. This key component is based on special crystals that exhibit the magneto-optical Faraday effect: When a magnetic field is applied, the polarization plane of incident light waves rotates in the crystal. Because of this Faraday rotation, reflected light – if any – can only return to the beam source in an extremely attenuated form. In this way, isolators protect the laser and ensure the narrow bandwidth of the lasers essential for quantum technology applications. To date, Faraday isolators have mostly been based on terbium gallium garnet (TGG), which has a high Verdet constant for visible and near-infrared light; this constant indicates the strength of the Faraday effect. "TGG isolators usually have a length of about 25 millimeters," reports Florian Rackerseider, project manager at Fraunhofer ILT. Miniaturization requires crystals with a higher Verdet constant that provide shielding in less space. These crystals for Faraday isolators were grown and tested in the HiPEQ project.

The team selected a material based on terbium(III) oxide (Tb_2O_3), which does not occur naturally. It has a Verdet constant three times higher than TGG and is particularly suitable for lasers in the blue wavelength range, for which no suitable material existed previously. "Growing monocrystalline Tb_2O_3 is a challenge," explains the expert, "because at melting temperatures above 2,500 °C, precise temperature gradients must be maintained during the transition to the stable phase." This refers to the transition from the molten ceramic starting material to the Tb_2O_3 crystal. The cooling rates are crucial for the quality of the crystal; the process is so sensitive that conventional crystal growth methods have never succeeded in producing Tb_2O_3 in the size and quality required for isolators. The engineers employed co-doping with lutetium oxide (Lu_2O_3) to stabilize the cubic phase in which the material is grown, and thereby simplify the growth process.

Laser technology as the key to growing high-purity crystals

In a HiPEQ subproject, SurfaceNet, Laserline, and Fraunhofer ILT have developed and implemented a new system in which $(Tb_xLu_{1-x})_2O_3$ isolator crystals are grown using the laser-based optical floating zone (LOFZ) process. The transition from molten ceramic to crystal takes place at the edge of the floating zone, which is surrounded by four processing optics. These direct the radiation from four diode lasers, each with a maximum optical power of 3 kW, onto the ceramic feed rod and melt it into a single crystal.

The irradiation – optimized in simulations with trapezoidal, extremely homogeneous beam profiles – ensures uniform heating power densities in the floating zone. The intensity distribution at the focus can be adjusted by modifying the beam path. "The trapezoidal geometry has an advantage: Most of the laser energy melts the ceramic and the rest regulates the temperature during solidification into a crystal," explains Rackerseder. In the continuous remelting process with a constant feed rate, the crystal may only leave the temperature range close to the melting point at precisely specified cooling rates. The team was able to meet this requirement using the precisely controlled LOFZ process. "For the first time, we are able to produce $(Tb_xLu_{1-x})_2O_3$ isolator crystals in the required size and quality," he explains.

Fully integrated system

In another subproject, the HiPEQ consortium integrated the new isolator crystals into modular miniaturized beam sources. Fraunhofer ILT also played a key role: Its team designed a fiber-chip coupler that can be individually adapted to different system designs and manufactured it from glass. The team achieved the necessary flexibility and precision with the help of selective laser-induced etching (SLE): A laser exposes microstructures in glass, which can then be etched out precisely, making it possible to create complex-shaped cavities inside the glass. In this project, the individual shaping of the SLE process was the key to manufacturing both beam sources with wavelengths of 461 nm (blue) and 637 nm (red) monolithically, even though components of different dimensions are installed in them. The Faraday isolator is integrated with the same precision as the interface from the PIC to the optical fibers, including coupling and outcoupling optics and beam splitters, which can be flexibly designed for the respective fiber diameters. The SLE process ensures that the different modules of both demonstrators are fitted with μm precision.

"The fact that the surrounding material has the same thermal expansion coefficient as the optical components makes the fiber chip coupler more resilient against temperature fluctuations," explains Sandra Borzek, who is responsible for this part of the project at Fraunhofer

ILT. Given the high precision requirements, stresses resulting from different material expansion are unacceptable. And there was another driver for the project approach: "Until now, laser beam sources for quantum technologies have mostly been adjusted manually," she explains. Each component is individually inserted and aligned, from the optics to the isolators and beam splitters to the fibers with single-digit μm diameters.

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The goal: minimized adjustment and assembly effort

Photonics is looking for solutions that minimize assembly and adjustment and maintain the required precision largely automatically. The packaging module, manufactured monolithically in a single SLE process, comes close to this. Ideally, after being equipped with the optical components, it serves as a fixed assembly that can be connected to the PIC using flip-chip bonding.

Originally, the SLE team wanted to manufacture the optics for coupling and outcoupling the light in the SLE process and polish them with a laser. However, it was impossible to polish the lenses in the component, and their surface was too rough after the SLE process. "So we developed various solutions to eliminate artifacts and residual waviness on the surfaces. This has brought us a big step closer to our goal of integrating the optics and polishing them," reports Borzek. The team decided to manufacture the optics in the SLE process without a fixed connection to the monolithic glass body. This allows them to be removed for polishing and then inserted back into exactly the same place from which they were removed.

HiPEQ has generated expertise for future beam sources

HiPEQ has achieved important milestones by successfully cultivating $(\text{Tb}_x\text{Lu}_{1-x})_2\text{O}_3$ isolator crystals, optimizing the process strategy for SLE-based optics manufacturing, and directly integrating microscopic coupling structures into the macroscopic housing. The consortium has gained the necessary expertise to implement flexible system designs with different isolators while significantly reducing the work needed for assembly and adjustment. "On this basis, we will be able to use the SLE process in the future to manufacture the glass packaging modules for flexible system designs with μm precision within days. The novel Faraday isolators are a key technology for further miniaturization," Borzek and Rackerseder are convinced. HiPEQ has improved the robustness and versatility of laser systems for quantum technology while reducing the adjustment needed.

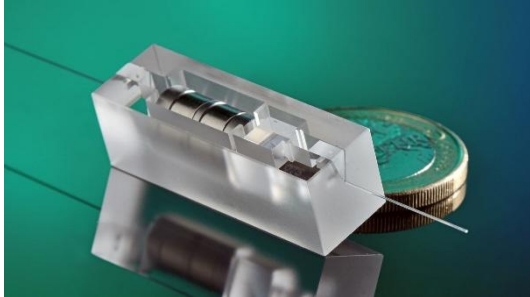


Image 1:

The packaging module – developed as part of the BMFTR-funded HiPEQ project and monolithically fabricated using the SLE (selective laser etching) process – integrates optics, an isolator, and a beam splitter within a very compact footprint and enables their alignment with micrometer precision.

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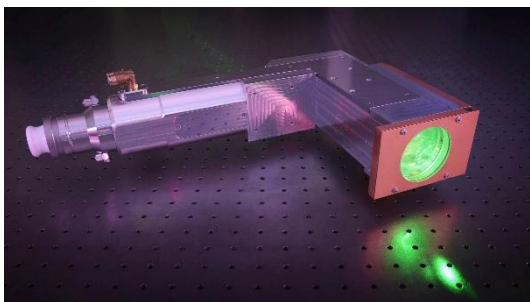


Image 2:

In the laser-based optical floating zone (LOFZ) process, four such processing optics developed at Fraunhofer ILT direct the radiation from four diode lasers, each with a maximum optical power of 3 kW, onto the ceramic seed rod and melt it into a single crystal. The optics ensure uniform heating power densities at the transition from the molten ceramic to the crystal.

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Image 3:

Novel Faraday isolators require special crystals of the necessary size and quality. For the first time ever, the project partners of the HiPEQ consortium have successfully grown novel terbium(III) oxide crystals co-doped with lutetium oxide.

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Image 4:

Using an SLE system from the associated project partner LightFab GmbH, the Fraunhofer ILT team was able to manufacture the packaging module with the required precision.

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