

The logo for visIT, with the word "visIT" in a white, lowercase, sans-serif font, followed by a short horizontal white line.

visIT
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Technologies for High-Energy Lasers and Applications

From the laser source to the impact on the target

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Topics

Editorial	3
Christelle Kieleck, Helge Bürsing, Karin Stein	
HELIKS – Pioneering high-energy laser research with a unique mobile investigation system	4
Helge Bürsing, Michael Henrichsen	
Optimizing target tracking for high-energy laser systems	6
Benjamin Göhler, Norbert Scherer-Negenborn	
Simulating atmospheric effects: A cloud chamber for laser propagation studies	8
Dirk Seiffer, Kathrin Kociok	
Comprehensive modeling of the propagation of high-energy laser beams	10
Adrian Azarian, Szymon Gladysz	
Adaptive optics for high-energy lasers	12
Szymon Gladysz, Andreas Zepp	
Coherent beam combining: Pushing the limits of HEL technology – Enhancing power and precision	14
Dieter Panitzek, Adrian Azarian	
Laser safety assessment for high-energy laser applications	16
Michael Henrichsen, Adrian Azarian	
Impact of directed high-energy lasers	18
Bastian Schwarz, Gunnar Ritt	
Components for monolithic fiber lasers	20
Michael Pisarik, Dieter Panitzek	
Silica and fluoride glass fiber research and development for high power laser and optronic applications	22
Jennifer Hartwigs, Pantelis Bourazanis	

Editorial

Dear friends of Fraunhofer IOSB,

High-energy lasers (HELs) are emerging as a disruptive technology and a game changer in both scientific research and defense applications. Key to this progress are advances in fiber lasers and beam combining. Initially confined to telecommunications, fiber lasers have been rapidly adopted across industries thanks to their compactness, high efficiency, and robustness. Moreover, they offer excellent beam quality and can be readily combined, enabling laser sources exceeding 100 kW. This opens new applications in a defense context. Unlike conventional weapon systems, HEL systems engage targets at the speed of light with great precision while drawing only electrical power. They therefore have an almost unlimited magazine and a cost per shot of only a few euros. They are ideal for tasks that require high accuracy, such as countering drones (UAVs/UAS).

In this issue of visIT, we share our insights into this technology and provide an overview of our expertise and ongoing projects, ranging from end-to-end system design, integration, and modeling to the development of novel materials and components for laser sources.

We begin with an article on our mobile high-energy laser system HELIKS with coherent beam coupling (CBC), which serves as a testbed to investigate scientific questions in laser safety, atmospheric laser propagation, and laser-matter interaction. Subsequent contributions explore tracking of objects such as drones; laser beam propagation through the atmosphere, including experiments in a cloud-chamber setup; beam control via adaptive optics; the investigation of potential hazards during HEL operation; and, finally, laser source development alongside the development of novel materials and components. We also show how HELIKS enables performance measurements in real-world environments, which in turn inform our full-system simulations that integrate all aspects of HEL systems. Only in this way can the full potential of HEL technology be unlocked for diverse defense applications.

We hope you find this issue both informative and enjoyable.

Fraunhofer IOSB, September 2025



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"HELIKS"

Pioneering high-energy laser research with a unique mobile investigation system



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Evaluating and optimizing the performance of high-energy laser systems is crucial for the future application of such systems in the fields of defense and civil security. In a world where the conflict landscape is changing dramatically and the use of unmanned aerial vehicles (UAVs) is increasing, new efficient and accurate countermeasures are required. High-energy lasers offer the potential to meet this need. However, there are several aspects that need further scientific investigation in order to bring such systems to a level of maturity that allows for widespread use. The following articles in this issue of visIT outline the necessary investigations into laser sources, target tracking, atmospheric propagation, laser effects and laser safety. To support and accelerate these investigations, a mobile high-energy laser system with coherent coupling, called HELIKS, is currently being set up at Fraunhofer IOSB.

Scope of the system

HELIKS is a state-of-the-art mobile and experimental laser system that has been designed in a flexible container format (see Figure 2). Its modular architecture allows for easy transportation to any location and seamless adaptation to specific experimental requirements. This enables a wide range of experimental configurations – even in environments without sufficient local infrastructure (e.g., power supply or LAN).

The system is modularly divided into different areas. The high-energy laser source and a customized battery are contained in the central container. A specially developed cooling system for the high-energy laser and the power supply complement the central laser system. The command-and-control room is housed in a separate container ensuring that the necessary laser protection requirements are met.

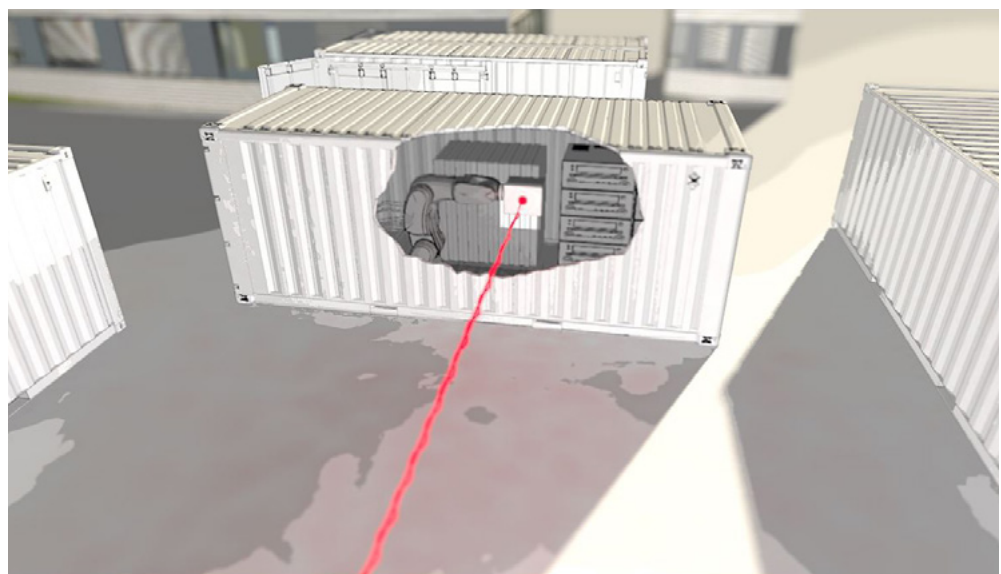


Fig. 1: 3D-sketch of the laser container.

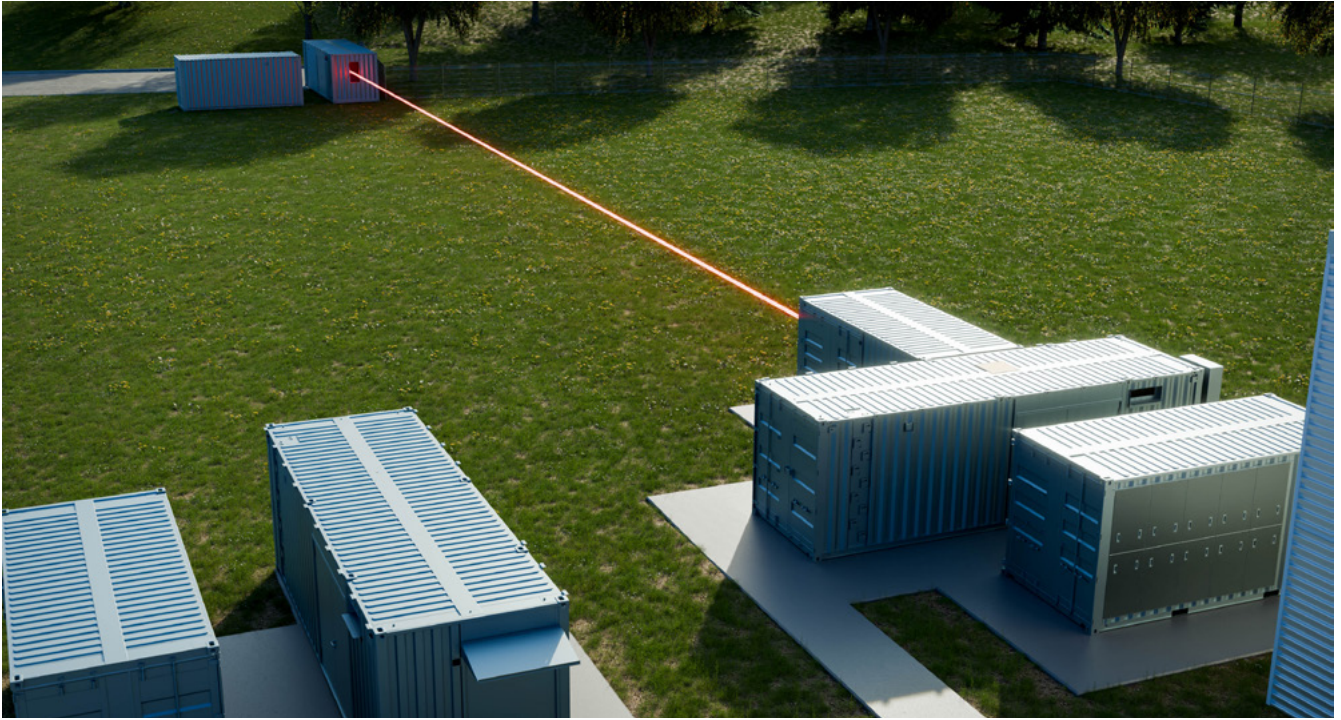


Fig. 2: Mobile container test setup of the high energy laser system HELIKS.

Another container houses the power distribution for the entire experimental container setups, including an emergency power generator to protect the laser system against power failures. It is also possible to operate the whole system standalone without local power supply.

HELIKS is supplemented by various measuring stations, which are housed in additional containers. Among other uses, these are employed to investigate laser effects, beam propagation and beam shaping through coherent coupling.

New and unique skills

HELIKS provides Fraunhofer IOSB with a laser system whose capabilities are currently unmatched in Germany. The system coherently couples over 90 laser beams, resulting in a total laser output power exceeding 100 kilowatts. Together with highly accurate beam shaping possibilities, this enables investigating the capabilities of most laser effectors currently under development in the corresponding configurations. The setup's high flexibility allows investigations to be carried out in different facilities and environments. This enables the collection of essential data to evaluate the effectiveness of such systems after the laser radiation has propagated through the atmosphere. Complete control over the phase of the laser beams allows for research of the advantages and disadvantages of this laser beam coupling method. Additionally, methods can

be developed to compensate for atmospheric effects such as turbulence, and different atmospheric conditions can be simulated by controlling the phase. This significantly expands the parameter space that can be investigated.

Thanks to its transportable and self-sufficient design, HELIKS provides additional insights into the mobile operation of directed high-energy laser systems as well as a basis for future laser safety considerations.

Technical data

A selection of HELIKS technical data:

- System fully transportable in containers
- Measuring containers for short and long-distance measurements
- Over 100 kW nominal laser power
- Over 90 phase-controllable laser beams
- Integral laser protection system
- Over 400 kW self-sufficient energy supply

Optimizing target tracking for high-energy laser systems



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HEL tracking concept

A high-energy laser (HEL) system does not only consist of the laser itself, but also sensors, illuminators, optics, controls and real-time algorithms. These are essential to obtain a precise tracking of the target, which is in turn a requirement to focus the HEL on the target long enough to have an impact.

Typical targets in a HEL combat scenario include small- to medium-sized objects that can move very quickly and dynamically against complex backgrounds, possibly even under poor visibility conditions. Therefore, a multi-stage tracking chain that leverages the advantages of different sensors is required before the actual HEL engagement can be started (example in Figure 1).

Typically, a radar sensor performs the task of large-scale air surveillance for the detection and coarse tracking of drones or approaching

RAM projectiles (rocket, artillery, mortar). An electro-optical or infrared (EO/IR) imaging sensor is then used to achieve more accurate target tracking, with a sufficiently large field of view (FOV) to compensate for inaccuracies in radar tracking. Finally, the high-precision fine tracking for determining and updating the HEL aiming point is carried out by a high-resolution sensor with narrow FOV. At Fraunhofer IOSB, active sensor systems with pulsed laser illumination and gated signal acquisition are designed, realized and assessed for this final stage to guarantee a robust target signature and a high target-to-background contrast.

Active imaging

Active imaging generally refers to sensor concepts with active scene illumination by a laser source and a corresponding camera capturing an image of the laser reflections.

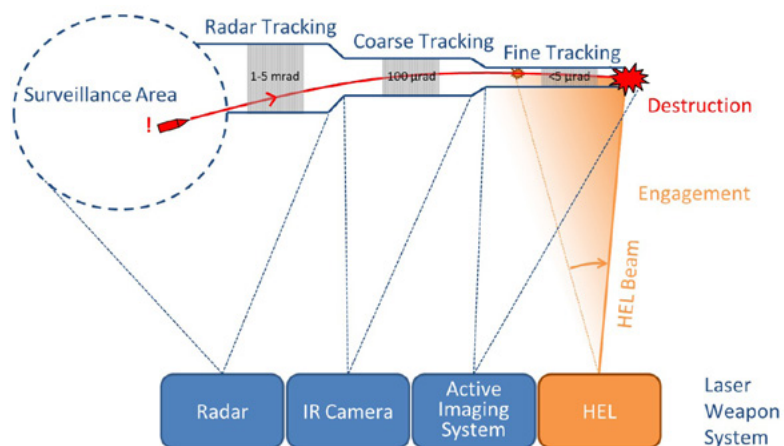


Fig. 1: Multi-stage tracking approach for a HEL engagement based on different sensor types.



Fig. 2: SWIR Gated Viewing example images of potential targets in a HEL engagement scenario captured during measurement campaigns with the system demonstrator of Fraunhofer IOSB: 120 mm mortar (left), 155 mm artillery grenade (middle) and Unmanned Aerial Vehicle (UAV, right) with indicated aiming points generated from appropriate fine tracking algorithms.

Gated Viewing in the short-wave infrared (SWIR) spectral range between 1 μm and 2.5 μm wavelength is a promising sensor concept [1]. Here, a short laser pulse is emitted in the direction of the target object and a highly sensitive and fast camera only captures the backscattered laser light from the immediate distance range around the target object. Interfering backscatter from the foreground and disturbing (cloud) backgrounds are suppressed, providing images with very high target-background contrast at long ranges and in adverse visibility conditions, also with 3D imaging capability (see examples in Figure 2).

LiDAR (Light Detection and Ranging) is another promising sensor concept for HEL detection and tracking. Especially the variant based on FMCW (Frequency-Modulated Continuous Wave), which is well-known from the radar field, is of interest. In addition to the distance information from a classical time-of-flight LiDAR, this approach determines the object velocity for each individual measurement point by analyzing the induced doppler shift. This provides valuable information about the target, e.g., for the detection, classification and tracking of UAVs. Since this approach is using coherent detection, it is also very robust against sunlight and background light.

Tracking algorithms

After detecting objects in single images – or more precisely, at different points in time – the tracking step is to correctly assign the objects from different points in time to each other. For this purpose, information from the appearance of the objects in the

images is used. This information depends strongly on the used detecting sensor. Therefore, the tracking algorithms are extremely diverse depending on the different sensors. In addition, pre-known information about the object itself and its behavior can be used to stabilize the tracking step.

The tracking step aggregates further information about the object, primarily its velocity and acceleration. This information is used to predict the object's behavior for bridging the unavoidable delays in the servo loop. On the other hand, a combination of many measurements of the object is used to reduce the statistical measurement error and thus improve the position accuracy of the object.

As said above, these results depend strongly on the selected sensors, so sensors and tracking algorithms must always be considered together.

Towards comprehensive HEL system evaluations

Combining imaging and tracking data is a necessary step towards performance evaluation of HEL systems. At Fraunhofer IOSB we are aiming to conduct these evaluations by developing a comprehensive system simulation that integrates tracking with the other HEL aspects, specifically laser-matter interaction and propagation. This approach enables comparisons, analyses, and assessments of HEL concepts in various tactical scenarios.

¹ Benjamin Göhler, Peter Lutzmann: "Review on short-wavelength infrared laser gated-viewing at Fraunhofer IOSB". Opt. Eng. 56(3), 031203 (2016), doi: 10.1117/1.OE.56.3.031203.

Comprehensive modeling of the propagation of high-energy laser beams



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As a laser beam travels through air, it encounters variations in temperature, pressure, and humidity, but also particles that can lead to beam distortion, scattering, and absorption. Overall, the beam loses energy as it propagates through the atmosphere compared to propagation in vacuum and becomes larger when it reaches the target. At Fraunhofer IOSB, we develop simulation tools for the propagation of high-energy laser (HEL) beams. We validate these tools using our own measurement techniques, which characterize the beam profile under the influence of the atmospheric effects.

HEL beams propagation simulation

Our HEL beams propagation simulation includes all relevant physical effects, which influence the intensity of the laser spot on a distant target. These encompass elements of laser physics (e.g., diffraction, beam quality etc.), and atmospheric effects, which are detailed here:

Turbulence

Temperature and density fluctuations in the atmosphere cause small refractive index changes along the propagation path that lead to deformations of the laser beam profile. An example of our simulation of a time-averaged beam profile affected primarily by turbulence can be seen in Figure 1 (left). Our turbulence models are being continuously updated to include different engagement scenarios. Although the presence of atmospheric turbulence is inevitable, mitigation methods exist and are called adaptive optics (see article on pp. 12-13).

Thermal Blooming

For HEL beams, heating of the air due to the absorbed laser energy significantly alters the refractive index of the air in the laser beam path. The resulting enlarging of the transverse laser beam profile is referred to as "thermal blooming". It depends mainly on the laser power and the effective absorption coefficient of the



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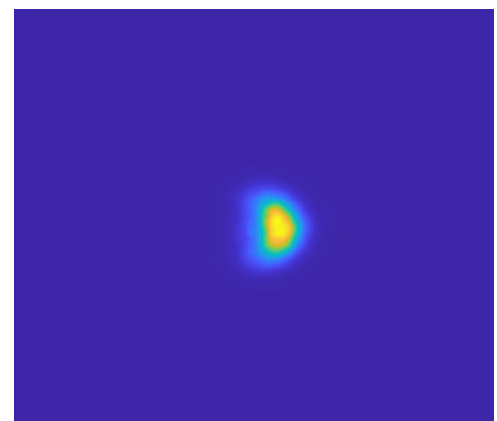
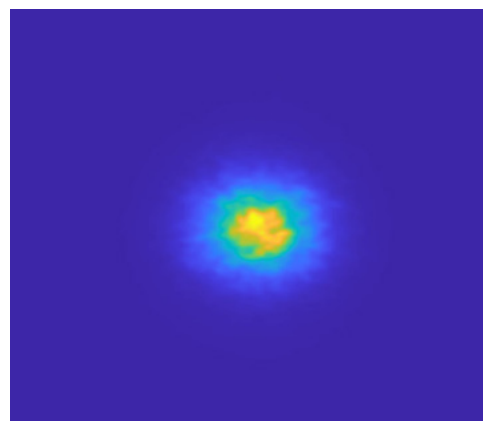


Fig. 1: Simulation of a beam affected by primarily atmospheric turbulence (left) and thermal blooming (right).



Fig. 2: Propagation experiment at Fraunhofer IOSB.

atmosphere but is also significantly (favorably) influenced by crosswind, which transports the heated air out of the laser beam's path. An example of our simulation of a beam affected primarily by thermal blooming can be seen in Figure 1 (right).

Extinction

The constituents of the air, i.e. molecules (H_2O , CO_2 , ...), aerosols, rain, and fog, absorb and scatter parts of the laser light. In the process of absorption, the energy content of a photon is absorbed and transformed into heat generating thermal blooming, while the scattering part leads to an attenuation of the laser beam power reaching the target.

Jitter

Mechanical vibrations of the platform on which the HEL is installed, which lead to fluctuations of the laser beam direction, are usually denoted as jitter. The frequency spectrum of jitter components depends on the explicit mechanical design of the beam director telescope and its connection to the host platform. Jitter leads to an additional increase of the time-averaged beam spot size on the target.

Data collection and study of the atmosphere

Real-world data collection is critically important to understand laser propagation (exemplified in Figure 2), for two main reasons: (1) to feed propagation models, and (2) to help define the best measurements to estimate atmospheric properties.

1. Propagation models for outdoor experiments rely on real-time data collection to accurately explain the results obtained.

A variety of measurements are required to attribute observed beam degradation to its causes: diffraction, turbulence, thermal blooming, extinction, and jitter. These measurements need to be done in real-time during the experiments, which is challenging considering that most measurements are always averaged over time and/or space.

2. For horizontal and ground-level propagations, measuring instruments can be placed along the entire propagation path. This, however, is not possible in other configurations, specifically for slant paths. Moreover, these instruments are not always available on the platforms on which a HEL is installed (like on vessels etc.). Therefore, we investigate alternative measurement methods needed for accurate modelling of atmospheric properties, especially turbulence, along these slant paths. One approach is to estimate the turbulence strength from meteorological data, another is to derive the turbulence strength aloft from the surface-layer measurements.

Laser weapon system designs need to rely on predictions coming from accurate and trusted models of the atmosphere. These models are also key to predicting performance in particular circumstances, or in future scenarios.

Conclusion

At Fraunhofer IOSB, we study laser physics as well as meteorology and optical turbulence. Only by combining these three aspects, our modelling tools can be validated and further developed to predict and assess the beam properties when it reaches a target.

Simulating atmospheric effects: A cloud chamber for laser propagation studies



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The propagation of laser radiation in the atmosphere is significantly influenced by the prevailing meteorological and physical conditions. In particular, scattering and absorption caused by aerosols, which appear in the form of fog and cloud layers, have a major impact on the transmission of the radiation (see Figure 1). These effects not only reduce the power reaching the target but can also pose a potential hazard due to scattering in undesired directions.

To develop and validate precise models that allow quantitative and reliable predictions of the interaction between laser radiation and the propagation medium, a comprehensive and reproducible meteorological characterization of atmospheric influences is required. While open-field experiments theoretically enable direct investigation under real-world conditions, the targeted reproduction of specific atmospheric states is severely limited by natural variability and restricted control capabilities.

In contrast to this, at Fraunhofer IOSB, we are currently designing and constructing a cloud chamber (see Figure 2) to simulate fog and cloud layers under precisely defined and reproducible conditions. The test chamber is designed in such a way that key atmospheric parameters – particularly pressure, temperature, and relative humidity – can be set and precisely controlled within defined and variable ranges. The actual test chamber will have a volume of approximately 35 m³. It will be possible to vary the temperature within the chamber in the range between –50 °C and +40 °C, while the pressure can be set between 100 and 1100 mbar.

By selectively choosing the initial conditions, different cloud structures at various ambient pressures – and thus at different altitudes – can be simulated. This makes it possible to generate water clouds (e.g., stratus or cumulus clouds), mixed-phase clouds, as well as pure ice clouds (e.g., cirrus clouds) in a controlled manner.



Fig. 1: Scattered light resulting from the interaction between laser and cloud structures (illustration).

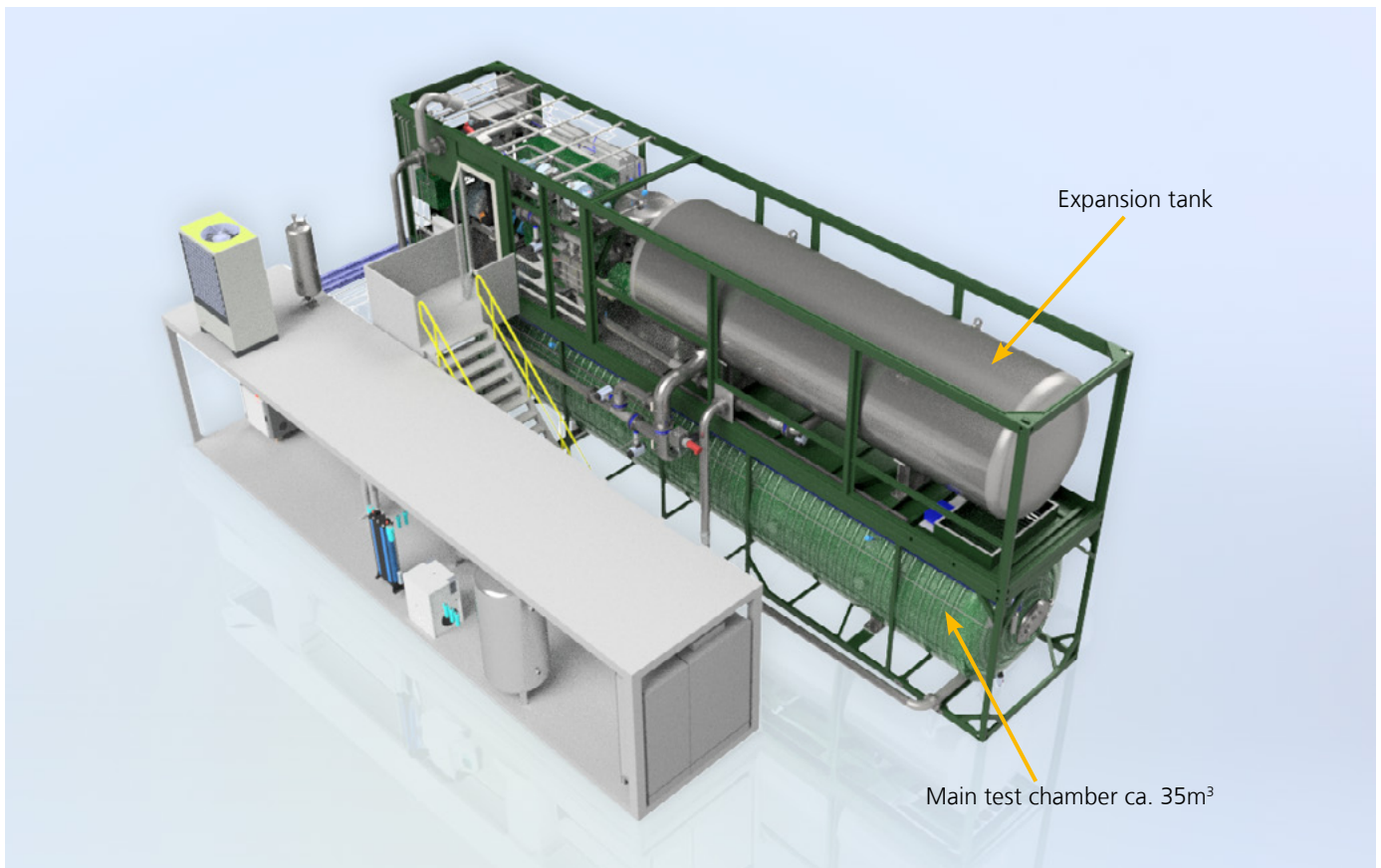


Fig. 2: Schematic representation of the adiabatic cloud chamber with main test chamber (lower tank) and auxiliary units.

The operating principle is based on a rapid drop in pressure within a moist gas environment, which leads to a sudden temperature decrease. The resulting supersaturation causes condensation and thereby the formation of fog or cloud droplets and, if applicable, ice crystals. The targeted introduction of condensation nuclei, such as aerosols like dust or pollen, serves to realistically simulate natural atmospheric processes.

The introduction of condensation nuclei into the test chamber is carried out by using a specially developed aerosol generator system that enables the production and controlled delivery of aerosols at defined concentrations. After being introduced into the test chamber, the natural formation process – from initial particles to larger aerosols and eventually cloud droplets – can be simulated in a reproducible manner.

To ensure continuous monitoring and precise analysis of aerosol composition, the test facility is equipped with a high-precision sampling unit. This allows for detailed characterization of aerosol particle sizes and concentrations during the experiment. In this way, exact control of experimental conditions can be ensured, and a direct correlation between atmospheric parameters and the observed scattering and absorption processes can be established.

The cloud chamber, currently under construction, and represents an important milestone for the systematic and reproducible investigation of atmospheric effects on laser beam propagation in general, and the propagation of high-energy lasers in particular.

Adaptive optics for high-energy lasers



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The optical properties of the atmosphere influence the propagation of laser radiation and can reduce the performance of laser systems: Atmospheric turbulence limits the achievable laser power at the target, the data rate of telecommunications systems, and the accuracy of target acquisition. In addition, the range at which all these systems can be used depends on the strength of the atmospheric turbulence through which a laser beam propagates (see article on high-energy laser propagation, pp. 8-9). This is why we at Fraunhofer IOSB analyze the limitations imposed by the atmosphere on laser systems, and develop solutions to suppress them.

Description of turbulence effects on an optical wavefront

The influence of atmospheric turbulence is measurable: The shape of the wavefront of the laser beam provides information about the

disturbances caused by the atmosphere. This wavefront is the surface on which all “rays” emitted simultaneously by the laser have the same propagation time. If all rays have traveled the same distance during this propagation time, the wavefront is a flat surface. This is the ideal case. If some beams pass through obstacles such as a glass block, they need more time to overcome the obstacle, so they cover a shorter distance in the same time. Then the wavefront is deformed. In the atmosphere, there are small areas of different temperatures and thus different refractive indices. Just like solid obstacles, these also lead to different velocities of light. Although the temperature differences are very small, they accumulate over the long distance through the atmosphere, and the resulting wavefront at the target is correspondingly strongly deformed.

This deformation can be broken down into individual aberrations. Each deformation can be represented as a sum of these aberrations



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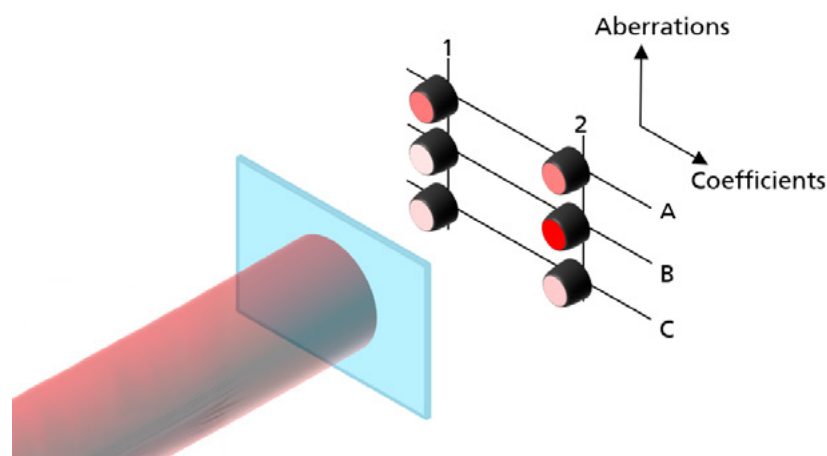


Fig. 1: Schematic of the holographic wavefront sensor, shown here for the measurement of three aberrations: defocus, astigmatism, and coma. Each row (A, B, or C) requires two detectors, such as photodiodes, to measure one of the three aberrations.

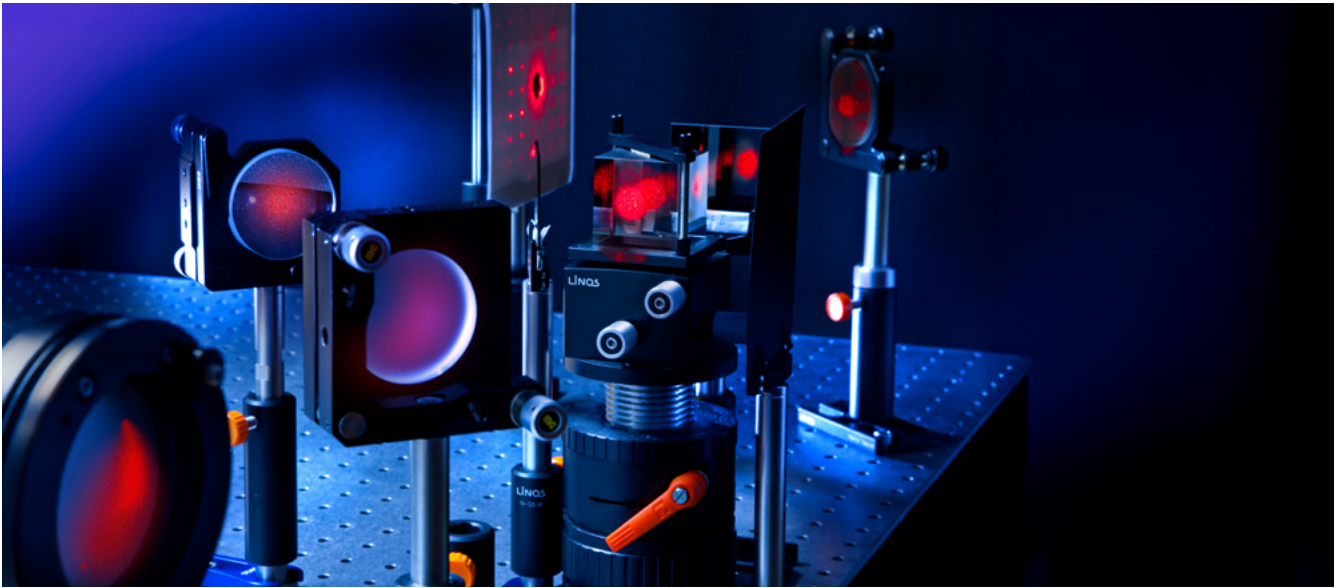


Fig. 2: Photograph of the holographic wavefront sensor in an experimental setup at Fraunhofer IOSB.

by selecting the strength of each aberration, i.e., its amplitude. The more aberrations are used to describe the wavefront, the more accurate the approximation to the actual deformation. The first aberrations, like defocus, astigmatism, and coma, have the greatest influence on accuracy; higher-order aberrations become less and less important for the approximation.

Measurement of the wavefront deformation

On the one hand, measurements of wavefront deformation can be used to make predictions for future experiments or applications: Under the given atmospheric conditions, deformation of the same order as the previously measured can be expected. On the other hand, real-time measurement can be used to directly correct for the influence of the atmosphere. The measurement signal is then converted into a control signal for a corrector. This corrector in turn additionally (pre-)deforms the wavefront of the outgoing laser beam: the beam now has the same deformation, but with a negative amplitude compared to the atmospherically induced aberration. In an ideal world, these deformations are then eliminated by the atmospheric turbulence.

There are different approaches and sensor types for measuring the wavefront of a laser beam. All of them are based on pure intensity measurements. For this purpose, the laser beam is divided into partial apertures in front of the detector using a microlens array or superimposed on a reference laser beam in the detector plane, thus generating a characteristic interference pattern.

Challenges and our solutions

A particular challenge for the measurements is that the conditions in the atmosphere change very quickly due to turbulence. A measurement of the deformation is no longer representative of the current state just milliseconds later. Wavefront measurement must therefore be performed at a very high repetition rate.

This is where commercial wavefront sensors reach their limits. One promising solution is the holographic wavefront sensor developed at Fraunhofer IOSB. At the heart of this device is a diffraction grating (see Figures 1 and 2). The sensor offers direct detection of the coefficients of individual aberrations by a simple contrast measurement. With only minor calculations needed, the sensor can in principle be operated at megahertz bandwidths, thus enabling extremely fast adaptive optics.

At our institute, we are also working on wavefront sensors to be used on uncooperative targets. In astronomy, wavefront sensors perform measurements on cooperative targets (stars, laser guide stars). In high-energy laser (HEL) applications, such "beacons" are not available. Wavefront measurement must be carried out from light reflected back off target surfaces, which immensely complicates the process and leads to high errors when traditional sensors are employed for this non-standard use. This is why we at Fraunhofer IOSB are also developing very high-speed interferometric sensors that can deal with target surface effects that masquerade as atmospheric aberrations. These and other types of (patented) wavefront sensors will soon be deployed in real-world demonstrators.

Coherent beam combining: Pushing the limits of HEL technology

Enhancing power and precision



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Fiber lasers are capable of delivering high output powers, reaching several kilowatts at a wavelength of 1 μm and up to one kilowatt at 2 μm , all while maintaining diffraction-limited beam quality. However, further power scaling from a single fiber laser is fundamentally constrained by the onset of optical nonlinearities, the thermal load caused by the laser process, and the fundamental damage threshold of fused silica, the standard material used in laser fibers.

To overcome these limitations, beam combining techniques are employed to merge the outputs of several fiber lasers or amplifiers. Coherent Beam Combining (CBC) stands out as an effective method for power scaling while preserving beam quality and thus increasing the irradiance (brightness). In addition, coherent beam combination is robust against single channel failure, as the overall power generation is divided into multiple parallel amplifiers

that work independently. Furthermore, CBC allows for atmospheric turbulence correction and beam fine-steering by phase control.

Compared to Spectral Beam Combining (SBC), CBC offers superior "power-in-the-bucket" efficiency at high laser power, particularly when implemented using a tiled-aperture configuration. Notably, in tiled-aperture CBC, efficiency does not degrade while the number of channels and overall output power increases, as schematically illustrated in Figure 1. Additionally, this method does not require a combining element, allowing the combined output power to scale to hundreds of kilowatts, depending on the number of contributing channels. Importantly, the combination efficiency is not degraded by the channel count, making it a promising solution for achieving ultimate power scaling in high-energy laser systems. CBC is therefore an important research topic for us.



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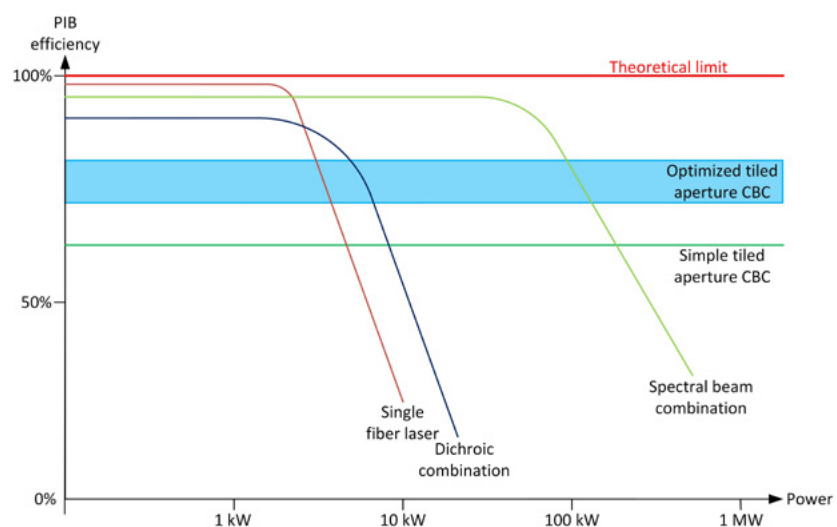


Fig. 1: Qualitative dependence of power-in-the-bucket efficiency vs. combined laser power for a single laser source and different combining schemes.

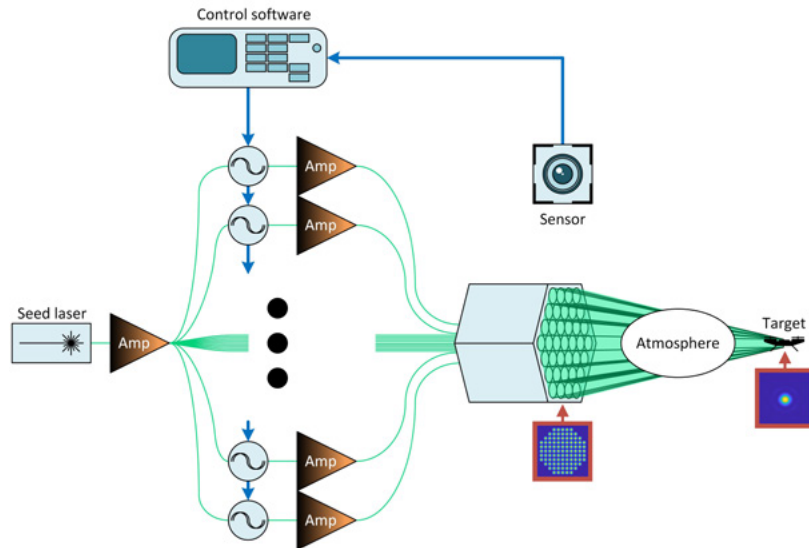


Fig. 2: Schematic of a CBC system.

Characteristics and capabilities of coherent beam combining

The output of a highly coherent fiber-coupled seed laser source is split into multiple fibers and amplified in parallel, see Figure 2. Controlling beam parameters such as phase, amplitude and polarization in each channel allows for efficient combining into an output beam. Components required for CBC, including fiber splitters, phase shifters and polarization controllers, can be used with low power as the output power of each channel will be amplified subsequently from milliwatt to kilowatt level. Afterwards, the different output fibers are arranged in a structure called phased array, which could have a hexagonal or square pattern, see inset in Figure 3.

As the mutual coherence of the channels is maintained, the output beams will interfere on the target. Furthermore, changing the phase of each channel causes changes in constructive and destructive interference. This allows the creation of a laser

spot on the target that is much smaller than the spot created by each individual channel, as can be seen in Figure 3. Moreover, the position of the created spot can be moved by applying a phase tilt on the phase shifters allowing for an electro-optical fine tracking capability without moving mechanical parts. By the coherent nature of this method, the intensity of the spot on the target is higher than just the sum of the intensities of each individual channel: The peak intensity scales instead with the square of the channel count.

Beam propagation aberrations caused by non-deterministic effects such as atmospheric turbulence can be corrected by applying a correction phase matrix to the phase shifters. In this context, we are investigating the application of a CBC fiber-based laser system at $1\ \mu\text{m}$ wavelength with respect to atmospheric effects and compensation at relevant laser powers. This allows us to benchmark and verify in-house-developed atmospheric propagation codes.

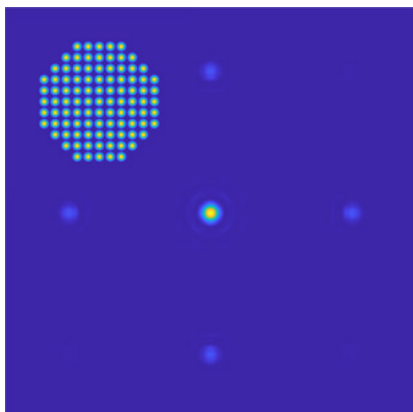


Fig.3: Power density distribution of a multi-channel CBC laser system in the near field (laser output) – upper-left insert, and in the far field (target area) with in-phase emission of all channels.

Addressing eye-safety by investigating $2\ \mu\text{m}$ CBC systems

Due to laser safety aspects, the deployment of high-energy lasers (HEL) is challenging, especially in urban environment. A scattered reflection of a beam at this power level can cause permanent eye damage, especially in the commercially widespread $1\ \mu\text{m}$ wavelength range. This is due to the transparency of the eye and its subsequent focusing onto the retina, where any damage is irreversible. Therefore, we additionally investigate CBC laser technology at $2\ \mu\text{m}$ wavelength that offers improved eye-safety. This radiation is absorbed primarily on the cornea and is not penetrating to the retina, thereby avoiding a factor 10^4 increase in intensity due to focusing. Therefore, the development of a CBC fiber-based system at $2\ \mu\text{m}$ wavelength is specifically considered.

Laser safety assessment for high-energy laser applications



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There are many hazards for military personnel and uninvolved third parties associated with the use of directed high-energy laser systems in open environment that differ from conventional weapon systems. Particular attention should be paid to potential skin burns and most notably damage to the eye. According to occupational safety rules, the level of radiation an unprotected person can be exposed to is defined by the Maximum Permissible Exposure (MPE) as specified in current regulations (e.g., the TROS [1] in Germany). Using the MPE and knowledge of the power, diameter and divergence of a laser beam, the potential laser hazard distance for eye exposure, known as the Nominal Ocular Hazard Distance (NOHD), can be calculated. However, much more information is required to estimate the NOHD for a given scenario involving a directed high-energy laser and to understand all the different potential hazards. Figure 1 shows the main

laser hazards, which can be divided into three categories:

- Direct irradiation from a laser beam
- Exposure to radiation scattered from air particles within the beam path
- Exposure to reflected radiation due to specular or diffuse reflections from the target or surroundings

Direct irradiation and scattered radiation

A comprehensive overview of the battlefield, as well as prior knowledge of civilian activities (e.g., air traffic and satellite movements), can help avoid direct irradiation. Scattered radiation has been shown to be relatively unproblematic for laser powers under 100 kilowatts. However, detailed knowledge of

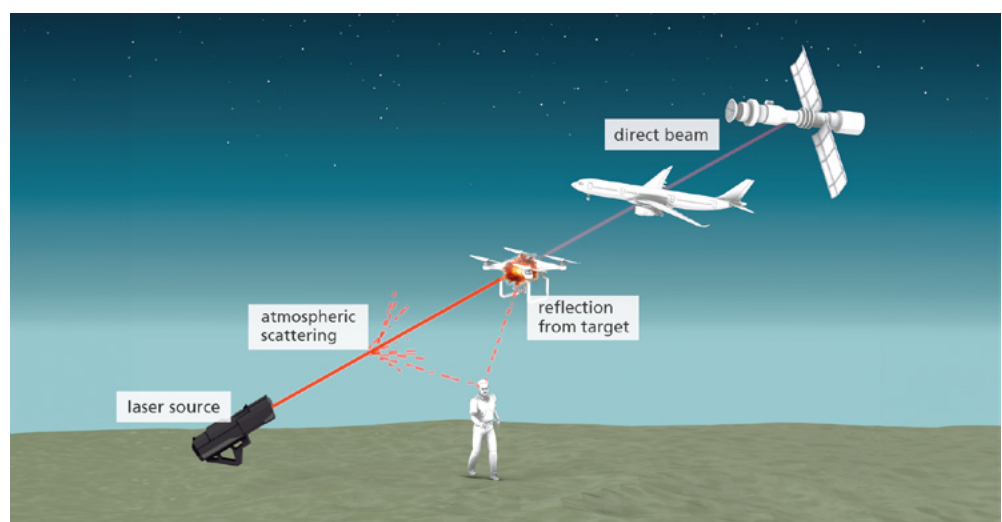


Fig. 1: Schematic illustration of the different hazard zones: 1. direct beam; 2. scattering from the atmosphere; 3. reflections from the target, e. g., drones.

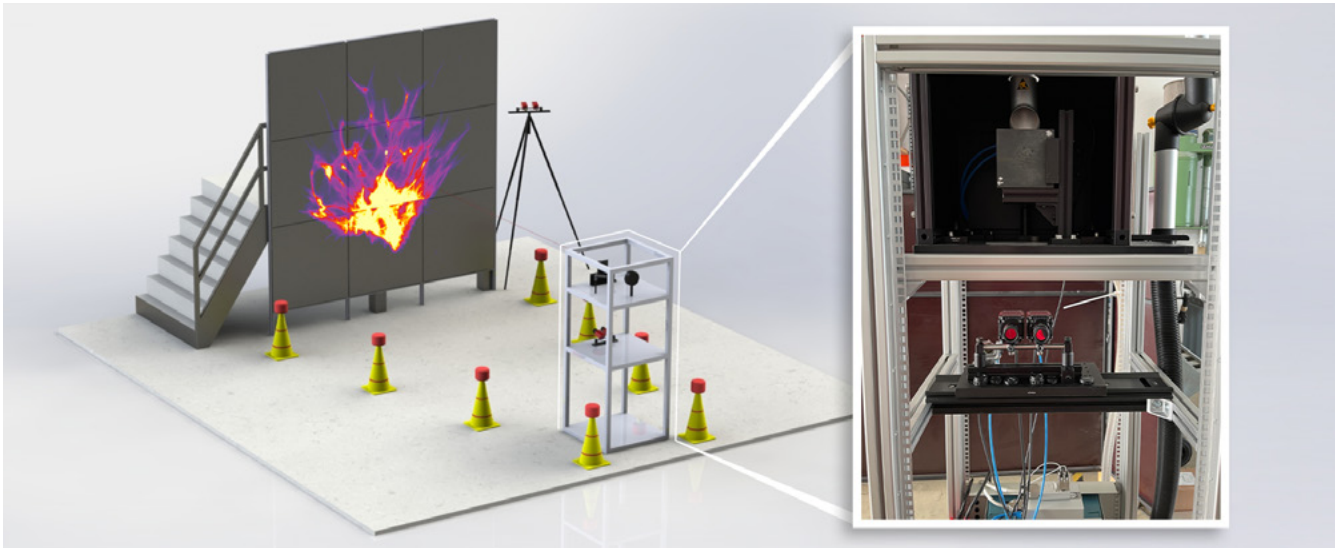


Fig. 2: Experimental setup used to monitor the reflections of a high-energy laser on a metallic surface. This setup can be used with lasers of various powers and wavelengths.

the laser propagation through the atmosphere is necessary to implement the most suitable measures. Our ability to provide this information is described in detail in the laser propagation section of this *visT* issue.

Reflections from the sea surface

Due to various reasons, directed high-energy lasers in German military are currently used primarily in maritime environments. In this environment, there is an additional hazard zone, because a laser beam that misses its target may be dynamically reflected off the sea surface. At Fraunhofer IOSB, we are developing and refining a simulation tool that can predict these reflections under different weather conditions [2]. We conduct maritime measurements in dynamic scenarios to further validate the simulations.

Reflections from a target

When a directed high-energy laser is used to engage targets, especially metallic ones, some of the laser light is reflected. This reflected light can pose a hazard to bystanders, military personnel and sensors. The target's reflection and scattering properties change dynamically during the engagement as its surface geometry and phase change (i.e., the target melts). During the initial phase of an engagement, the reflected intensity is primarily scattered and may also have a specular

component. However, as the target's temperature increases and it possibly begins to melt, the reflected intensity can consist of caustics, which rapidly change shape and are unpredictable. These uncontrollable laser reflections can limit the use of directed high-energy lasers in an outdoor environment, such as during trials or training.

Traditional methods of measuring material reflections (specifically the bidirectional reflectance distribution function BRDF) are impractical for measurements of materials with rapidly changing surface properties. To measure the dynamically changing BRDFs from a directed high-energy laser beam irradiating different targets, we developed a novel experimental setup (see Figure 2) that captures the spatial and temporal variations of these reflections on a witness screen. The reflections are then imaged by different cameras. Using this technique, we can measure the dynamic BRDFs of various targets under high irradiance [3].

Our studies aim to develop reflection models that can be incorporated into deterministic or probabilistic risk and hazard assessment tools. It should be noted that, in contrast to conventional weapons for which well-developed and accepted safety and risk analyses are available, there is still no consensus on concepts for safety and risk analyses with directed high-energy lasers. Therefore, gathering the necessary scientific data to quantify the probability and impact of directed high-energy laser-related hazards is crucial.

¹ TROS = Technische Regel zur Arbeitsschutzverordnung zu künstlicher optischer Strahlung (equivalent to the ANSI rules on safe use of lasers in the USA).

² F. Schwenger, A. Azarian und M. Henrichsen, "Simulation of the reflection of a high energy laser beam at the sea surface for hazard and risk analyses," *Applied optics* 63 (14), 2024, doi: 10.1364/AO.516715.

³ M. Henrichsen, B. Schwarz, G. Ritt, A. Azarian und B. Eberle, "Laser safety assessments supported by analyses of reflections from metallic targets irradiated by high-power laser light," *Applied optics* 60 (22), 2021, doi: 10.1364/AO.424722.

Impact of directed high-energy lasers



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Directed high-energy lasers will evolve in the near future from pure technological demonstrators to serious actors on the battlefield. Unlike conventional weapon systems, high-energy lasers (HELs) engage their targets at the speed of light but require time to have the intended effect. This is because the interaction mechanism involves heating the material. By keeping the laser on the same spot on the target, a constant input of thermal energy on that spot is created. The material can start to melt or vaporize, resulting in a hole being drilled in the material until it is perforated. Many parameters of the laser, e.g., laser power, laser spot size on the target or laser wavelength, influence how quickly this process takes place. Fraunhofer IOSB has unique capabilities to investigate such processes both theoretically and experimentally, in the laboratory as well as under realistic field conditions.

Laser-interaction with optics and optoelectronic elements

At Fraunhofer IOSB, we investigate laser-induced damage of optics and optoelectronic elements which can occur via "in-band" or "out-of-band" wavelengths [1]. In-band wavelengths pass through the optics and are focused onto the detector, causing damage at relatively low laser power due to the small heated volume (see Figure 1). Out-of-band wavelengths, however, are strongly absorbed by the sensor's optical elements or mechanical structures outside their transmission window, requiring higher power to heat a larger area or volume.

With the advent of compact high-energy lasers, it has become feasible to directly irradiate camera optics from longer distances, degrading sensor performance without necessarily damaging



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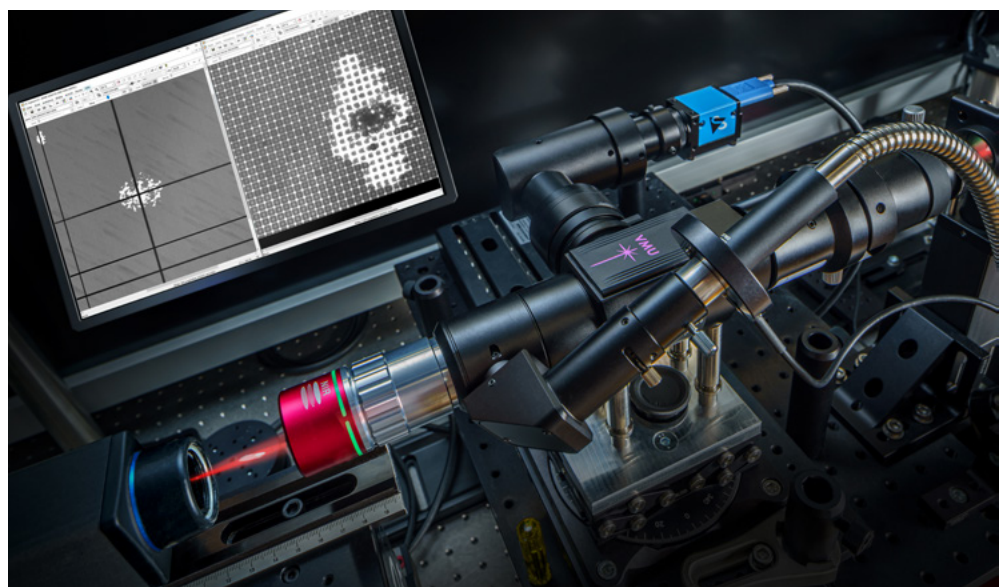


Fig. 1: Measurement setup for the analysis of damage thresholds in optoelectronic systems.



Fig. 2: Collage of laser irradiation experiments on different target materials: metal, plastic, bolometer, and mirror.

the detector itself. For example, infrared (IR) optics in thermal imaging cameras are transparent in the thermal IR range but absorb near-infrared (NIR) radiation. High-power NIR irradiation of these optics can initially cause severe image contrast reduction and thus degrade the overall system performance. Continued exposure may lead to physical damage of the optics, indirectly impairing the sensor.

The effectiveness of in-band versus out-of-band damage depends on sensor-specific factors such as detector type, material properties, optical design, and available laser power and intensity. Investigations on out-of-band damage thresholds – using IR materials common in camera optics and NIR lasers – are essential for fully understanding the vulnerability of optoelectronic imaging sensors to laser threats.

Laser-interaction with solid materials

Measuring the perforation times of different materials, such as steel and polyamide, is complex. However, at Fraunhofer IOSB this is feasible due to state-of-the-art experimental facilities like our high-energy laser investigation system HELIKS (pp. 4-5). Figure 2 shows different targets irradiated with a high-energy laser. Furthermore, it is also important to investigate which laser wavelengths are best suited to a particular material, as this strongly influences the efficiency of energy absorption and material damage [2]. High temperatures can alter the mechanical properties of a material and may result in the loss of its strength. For example, materials like metals and polyamide can

experience significant weakening when exposed to elevated temperatures, which could lead to the failure of critical components, such as helicopter blades, even before any material is physically removed.

Countering high-energy lasers

Smooth metallic surfaces are sometimes considered a possible protection against high-energy lasers. However, their high power density can perforate even polished metals. Only special dielectric mirrors may withstand it, yet they are angle- and wavelength-specific. Dust on mirror surfaces absorbs the beam and leads to material failure. Countering high-energy lasers will require new approaches that can be divided into two categories: active and passive. Active approaches would include disturbing the propagation of the beam or the targeting, for example using a smoke screen. Passive approaches would include hardening potential targets, for example by adding layers of materials with specific properties, e.g., thermal barrier coatings. Fraunhofer IOSB investigations focus on optimizing both active and passive defense strategies evaluating their effectiveness in real-world scenarios. By developing innovative solutions tailored to specific threat scenarios, the institute aims to significantly improve the protective measures available for critical systems and infrastructures.

- 1 B. Schwarz, G. Ritt und B. Eberle: »Impact of threshold assessment methods in laser-induced damage measurements using the examples of CCD, CMOS, and DMD«. Applied Optics, Jg. 60, Nr. 22, F39-F49, 2021, doi: 10.1364/AO.423791.
- 2 C. Romano, G. Ritt, M. Henrichsen, M. Eichhorn und C. Kieleck: »Investigation of the polymer material perforation time: comparison between two fiber laser wavelengths«. J Polym Res, Jg. 31, Nr. 2, 2024, doi: 10.1007/s10965-024-03885-w.

Components for monolithic high-power fiber lasers



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Fiber laser components are necessary for the realization of high-power monolithic fiber lasers. A monolithic fiber architecture contains only fibers and fiber components spliced together to form a single glass structure without free-space optics. This offers a robust fiber laser design that is intrinsically resistant to mechanical vibration, shock and particle contamination. Furthermore, monolithic fiber lasers show no thermal drift, and they are maintenance-free so that subsequent alignment is not needed. At Fraunhofer IOSB we therefore investigate and optimize critical fiber laser components for various functions and fiber laser systems.

Such a critical component is, for example, a fiber-based pump-signal combiner, which merges pump beams from multiple multimode fibers with a seed signal from a single-mode fiber into an active double-clad fiber. Within this active fiber, the pump beams are used to amplify the seed signal. Various architectures exist for pump-signal combiners. Fraunhofer IOSB focuses on pump-signal combiners based on end-pumping topologies that maximize the pump power handling while maintaining diffraction-limited beam quality.

Pump-signal combiners

A pump-signal combiner consists of two primary structural sections (see Figure 1): The input side that consists of a geometrical arrangement of multiple multimode pump fibers surrounding a central single-mode (or few-mode) signal fiber, and the output side that consists of a double-clad fiber where pump and signal beams are confined to the fiber cladding and core, respectively.

To efficiently transfer pump power into the double-clad fiber, the input fiber bundle (including the central signal fiber) is often tapered. This tapering helps to match the outer diameters of the bundle and double-clad output fiber. However, tapering also changes the mode field diameter of the signal fiber that must be considered for minimal signal losses.

Designing high-power pump-signal combiners requires to balance an efficient pump and signal coupling with the preservation of the beam quality. Any uncoupled signal or pump power can result in internal heating of the combiner, limiting power handling due

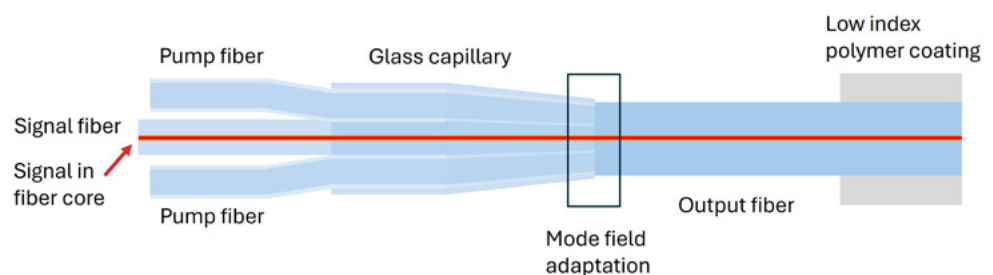


Fig. 1: Schematic of an all-fiber pump-signal combiner.



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Fig. 2: All-fiber pump-signal combiner developed at IOSB.

to thermal constraints. To manage this, numerical simulations are essential. They allow for accurate thermal modeling and help to optimize both the internal structure and external housing of the component. These models also enable performance predictions under various environmental conditions.

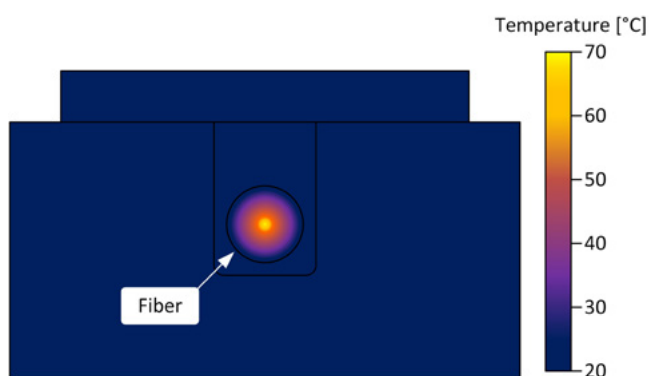


Fig. 3: Temperature simulation in an all-fiber pump-signal combiner.

During development, we use specialized measurement equipment for in-situ monitoring and parameter optimization. Final components are tested using Fraunhofer IOSB's own state-of-the-art fiber laser systems to ensure they are fulfilling the demands of high-power applications.

The institute has successfully manufactured pump-signal combiners, like the one shown in Figure 2, capable of handling kilowatts of pump power and transmitting hundreds of watts of signal power, meeting the stringent requirements of modern high-power fiber amplifiers. We have developed accurate numerical models for designing high-performance fiber laser components, particularly for thermal management and operational prediction, as shown in Figure 3.

Partners and customers

Fraunhofer IOSB offers development and manufacturing of fiber components like combiners, strippers, tapers, and many others for the SWIR spectral range, for internal fiber laser development and industrial partners. With increasingly varying reliability of global supply chains, long lead times, and limited access to components, research and development at Fraunhofer IOSB aims to build, support, and maintain a secure supply chain of state-of-the-art fiber components in Germany and Europe. Furthermore, it offers extensive feasibility studies, prototyping and simulation, and provides technology transfer for industrial partners.

Silica and fluoride glass fiber research and development for high power laser and optronic applications



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Silica-based optical fibers have long been used in the development of fiber lasers and amplifiers due to their excellent transparency, mechanical strength and compatibility with existing fiber technologies. Rare-earth (RE) doped silica fibers including Er^{3+} , Tm^{3+} , Yb^{3+} , and Ho^{3+} are of particular interest for industrial applications due to their ability to deliver high output power with excellent beam quality. However, in recent years, the growing demand for high-power lasers in the kilowatt range and operating in the short-wavelength infrared (SWIR) wavelength range at $2\text{ }\mu\text{m}$ has highlighted the need for the development of specialty silica fibers that are currently not available on the market.

For other optronic applications, however, silica-based fibers exhibit limitations such as a restricted transmission window in the upper SWIR beyond $2.1\text{ }\mu\text{m}$ and towards the mid-IR beyond

$3\text{ }\mu\text{m}$. To overcome these limitations, active and passive fluoride glass fibers have been developed. Their lower phonon energy and greater transparency in the mid-IR range makes them an excellent candidate for mid-IR fiber lasers. Active fluoride fibers can also be fabricated by doping with rare-earth ions such as Er^{3+} , Ho^{3+} and Tm^{3+} . The doping concentration of RE ions in fluoride glasses can be higher than in silicates, which allows for specific optical signal emission and amplification.

At the Fraunhofer IOSB site in Oberkochen, our mission is to advance the research and development of doped and structured optical fibers. With the launch of our new facility, Fraunhofer IOSB possesses the capability to produce next-generation, custom-designed silica-based fibers tailored for high-energy laser applications as well as passive and active fluoride glass fibers to generate wavelengths in



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Fig. 1: Spooled fiber and three different fiber preforms from the fiber drawing process.

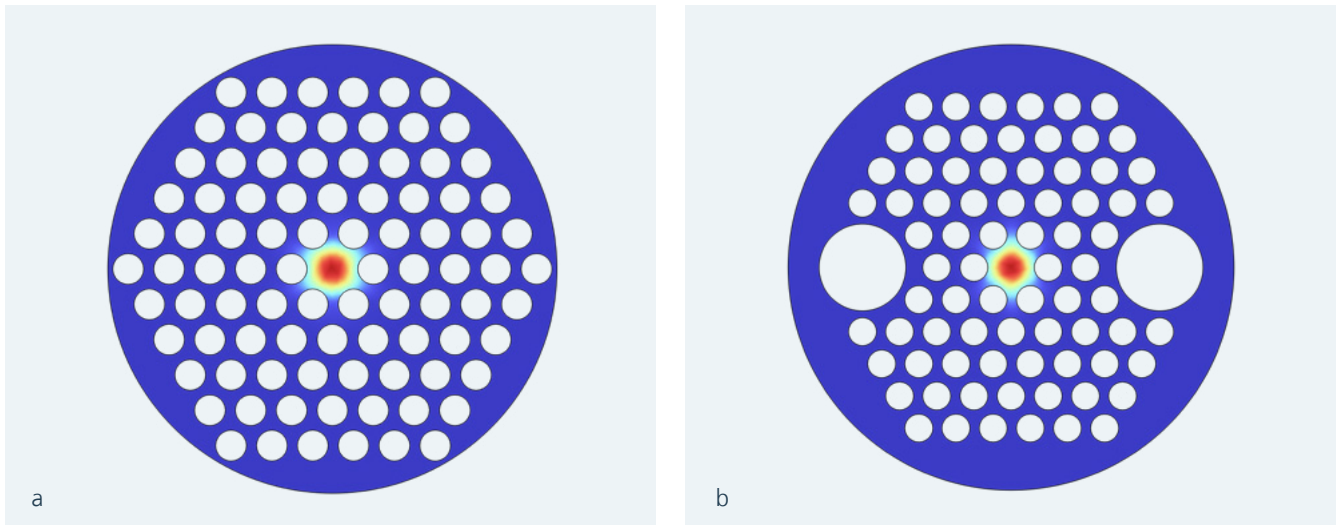


Fig. 2: Simulation of a fundamental mode within the cross-section of an Endlessly Single Mode PCF (a) and of a Polarization-Maintaining LMA PCF (b).

the mid-IR. Working closely with our fiber laser research team located in Ettlingen presents a key opportunity and opens new possibilities for research, development, and improvement of fiber laser performance.

Silica-based preforms and fibers

From the development of novel preforms to fiber drawing and advanced post-processing techniques, we provide a complete customization of silica-based fiber designs for needs that are not served by the commercial market. Our state-of-the-art ISO Class 6 cleanroom is equipped with a Modified Chemical Vapor Deposition (MCVD) system for in-situ solution doping and vapor-phase fabrication of RE-doped preforms. This enables the production of high-power laser fibers in the kilowatt range. Housed at the heart of our facility is a dual-sided fiber drawing tower, engineered to process all types of optical preforms. A typical drawn fiber with several preform examples can be seen in Figure 1. Throughout every stage of fabrication, preform and fiber quality is rigorously assessed using a suite of post-processing and characterization tools. Our specialized fiber fabrication processes cover both active and passive fiber designs, including – but not limited to – large mode area (LMA) fibers, photonic crystal fibers (PCFs), microstructured fibers, spun fibers, and double- or triple-clad configurations. Illustrated in Figure 2 are examples of such fiber structure designs, and their fundamental mode, for a PCF and an LMA PCF. Furthermore, we also are capable of a wide range of fiber coating options, from thermally and UV-cured polymers to robust metal coatings well-suited for demanding environments.

Fluoride glass and fluoride fibers

In addition to silica-based fibers, state-of-the-art technology is implemented at Fraunhofer IOSB in Oberkochen to develop specialized active and passive optical fluoride fibers of various geometries, including microstructured and other custom designs. On-site, we will investigate and fabricate these fibers from internally fabricated glass preforms consisting of specially formulated core and surrounding cladding glasses. For the successful fabrication of fluoride fibers, the glass preform should be of high quality. Therefore, to ensure this standard is met, we employ a wide range of modern characterization devices, including Raman and FTIR spectrometers, UV-Vis spectrometer, simultaneous thermal analyzer (STA), scanning electron microscope (SEM), preform analyzer, horizontal dilatometer, ultrasonic echometer, etc. After the fluoride glass preforms are characterized, they are drawn into a fiber on our fluoride fiber drawing tower.

Research services for partners and customers

The scientific knowledge and expertise gained from research and development of active and passive optical fibers will be used for our own fiber laser research and development, as well as for collaborative research projects with partners and external customers.

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