Fraunhofer IPM

Fraunhofer Institute for Physical Measurement Techniques IPM

**Annual report 2023/2024**

# Measuring • Monitoring • Optimizing

*<< **Cover**: Thermopiles can be used for contactless temperature measurement. Fraunhofer IPM is developing highly sensitive thermopiles based on novel thermoelectric materials using MEMS technology.*

Annual report 2023/2024

# Measuring · Monitoring · Optimizing

**"Measurement technology has many benefits: It ensures greater safety, quality and efficiency."**

Professor Karsten Buse, Director

# Measurement technology for safety

**Dear customers,
dear partners,**

Companies invest in Fraunhofer IPM measurement technology for quality assurance, waste and reject minimization, resource efficiency and product protection – either for their own use or for the series production and marketing of devices developed for this purpose. This brings financial benefits, too: They usually generate a quick return on investment (ROI), typically within one year. Another compelling reason for using measurement technology, which is often overlooked, is the prevention of technical risks. Here, too, investment pays off quickly. Interestingly, all three in-depth case studies in this annual report had the goal of preventing technical risks.

Flawless mechanical components are essential for the safe operation of machines. For example, a cast brake caliper on a car must be fitted with all the support hooks to ensure that sudden failure is completely eliminated. It needs to be subjected to a 100 percent 3D inspection, which can now be done efficiently, thanks to our free-fall measurement technology. This can prevent expensive recalls and reduce liability insurance premiums.

To ensure nobody is ever buried under bricks, the law provides for tunnels to undergo regular inspections. To this day, experts use hammers to tap the surface of the tunnel inch by inch, often from mobile scaffolds, "listening" for defects. This is subjective and takes time and money. Now we hammer using pulsed lasers and measure with laser microphones. Optical impact hammer tests are faster and more accurate – which saves money – all the while ensuring higher quality and safety.

When it comes to the energy transition, we continue to rely on chemical energy carriers. More and more frequently, fossil substances are replaced by hydrogen. Energy is also stored as electricity in batteries. What we must keep in mind is that if stored energy is released suddenly, this will reduce the immediate vicinity of the storage device to rubble. To prevent this from happening, technical areas need to be constantly monitored for leaks using hydrogen sensors. This applies to the hydrogen infrastructure as a whole, but also to fuel cells and electrical batteries, which can also release hydrogen. This is where our integrated thermal conductivity hydrogen sensors come in. They also deliver a positive ROI: fewer manual mea-sure ments, lower insurance premiums, and increased product sales thanks to the minimized risk achieved by a built-in monitoring system.

The term safety plays a key role across the board: The "functional safety" of our measurement systems must be guaranteed at all times. Our sensors monitor themselves and report any malfunctions – though fortunately this rarely happens!

Keeping the people using the measurement technology safe is also a priority. Our systems measure steel girders that are still extremely hot. They are integrated in production lines that transfer steel blanks at high speed and are also used on trains, in mines, in reactors, in mine gas channels and many other inhospitable environments. To this day, they are often carried and operated by people. To improve occupational safety, we are investing heavily in autonomous measurement robotics – which has the additional advantage of benefiting our customers' ROI. Robots that are able to move through entire structures, crawl through channels and perform measurements in factories without taking damage will become a integral part of our measurement system portfolio. So don't be surprised if you see driverless test systems moving about when you visit our institute. They're part of our team and they don't bite. If you would like to learn more about this topic, you've come to the right place!

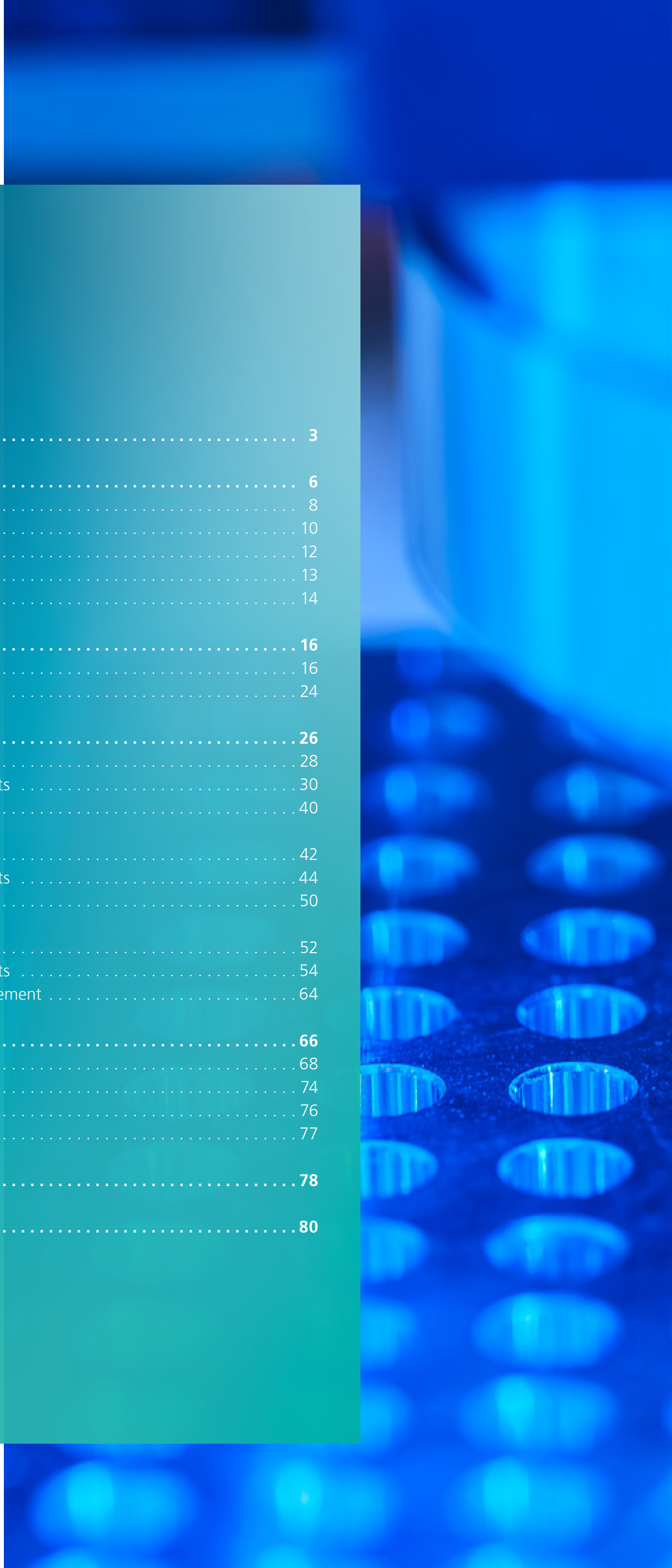
Be sure to subscribe to our monthly newsletter and our social media channels, especially LinkedIn, to make sure you don't miss anything!

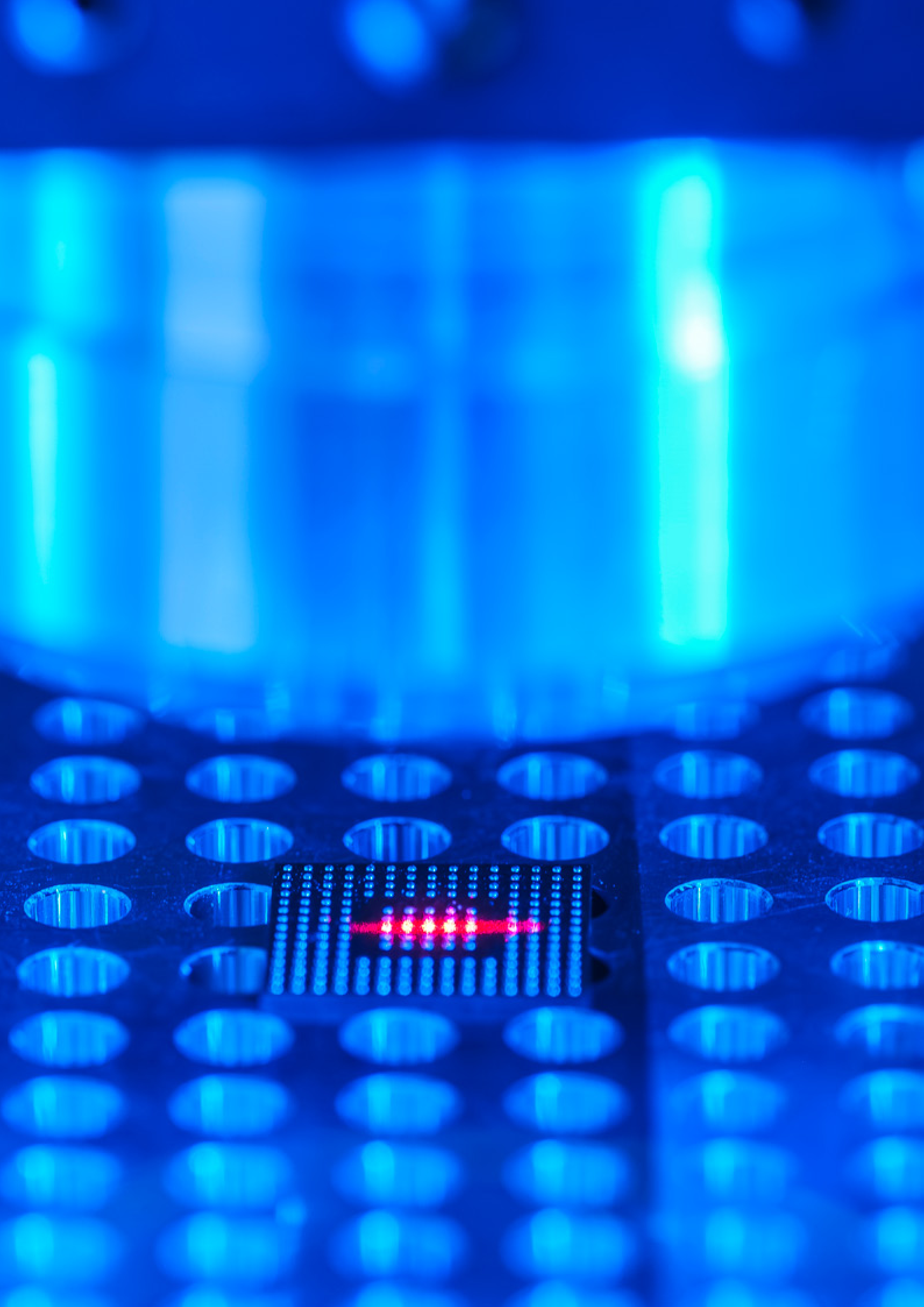
Stay safe in everything you do, preferably with our support.

*Professor Karsten Buse, Director*

# Content



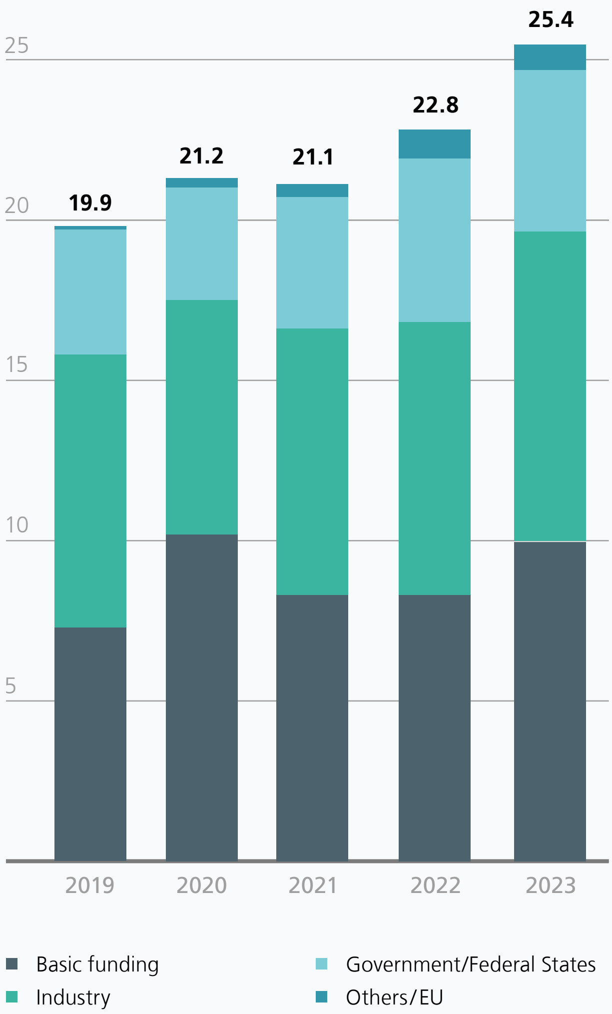




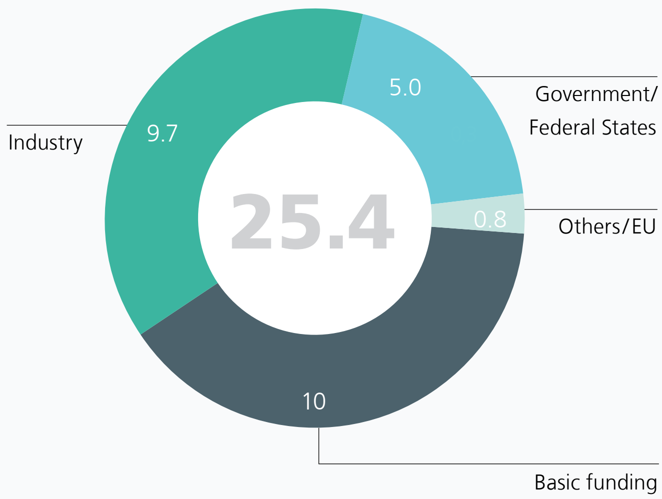
# **Overview** Fraunhofer IPM

# **Figures** Fraunhofer IPM

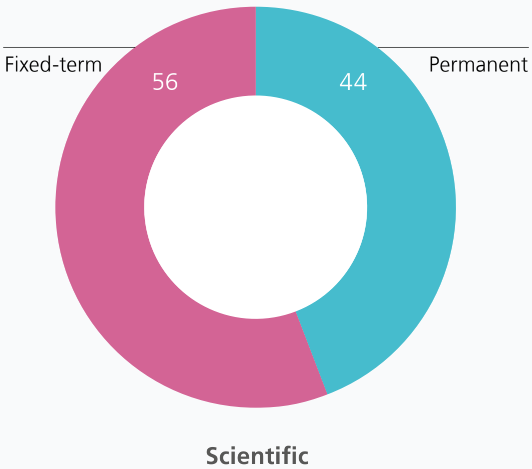

**Development** Operating budget in million euros

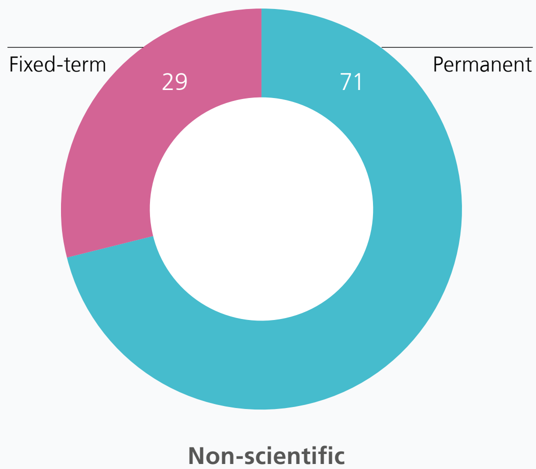



**Operating budget** 2023 in million euros

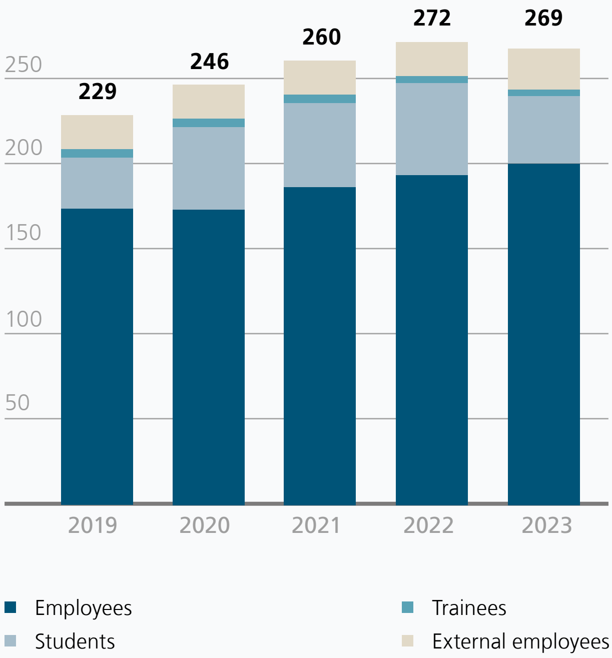


**Staff under the terms of the Collective Agreement for the Public Service TVöD**
Percentages of fixed-term/permanent contracts of employment 2023

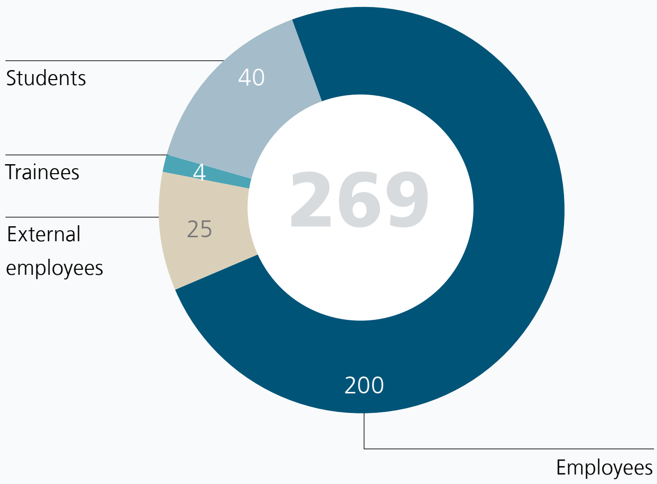



**Development** Number of employees




**Employees** 2023



# Organization

## MANAGEMENT

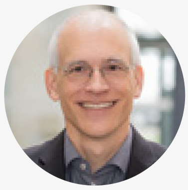
**Director**

Prof. Dr. Karsten Buse

Deputy Director

Dr. Daniel Carl

## COMMUNICATIONS AND MEDIA



**Head of Communications and Media**

Holger Kock

## ADMINISTRATION AND IT

**Head of Administration**

Wolfgang Oesterling

Administration

Sabine Gabele

Information and Communications Technology

Gerd Kühner

Recruiting and Human Resource Development

Saskia Sailer

## TECHNICAL SERVICES

**Head of Technical Services**

Clemens Faller

Mechanics and Construction

Thomas Hinrichs

Technical Equipment and Maintenance

Benjamin Schlegel

Research and Strategy

Dr. Milena Hugenschmidt

Organizational Development

Dr. Heinrich Stülpnagel

## PRODUCTION CONTROL Page 28

**Head of Department**

Dr. Daniel Carl

Optical Surface Analytics

Dr. Alexander Blättermann

Inline Vision Systems

Dr. Tobias Schmid-Schirling

Geometrical Inline Measurement Systems

Dr. Alexander Bertz

## OBJECT AND SHAPE DETECTION Page 42

**Head of Department**

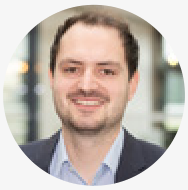
Prof. Dr. Alexander Reiterer

Mobile Terrestrial Scanning

Dr. Philipp von Olshausen

Airborne and Underwater Scanning

Dr. Christoph Werner

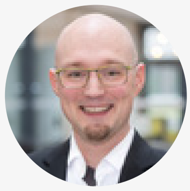


Autonomous Measurement Robotics

Dominik Merkle

Railway Measurement Techniques

Dr. Kira Zschiesche



3D Geodata Analytics

Benedikt Rombach

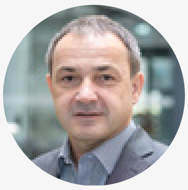
## GAS AND PROCESS TECHNOLOGY Page 52

**Head of Department**

Prof. Dr. Jürgen Wöllenstein

Integrated Sensor Systems

Dr. Benedikt Bierer



Spectroscopy and Process Analytics

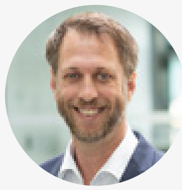
Dr. Raimund Brunner

Thermal Measurement Techniques and Systems

Dr. Katrin Schmitt

Nonlinear Optics and Quantum Sensing

PD Dr. Frank Kühnemann



Caloric Systems

Dr. Kilian Bartholomé

# **Advisory Board** Keeping us on track

**Our highly qualified advisory board guides and supports us in shaping our strategic direction and future goals. Once a year, the advisory board holds a meeting in Freiburg, which is also attended by representatives of the Fraunhofer-Gesellschaft.**

## Chairman

*Until 6/30/2024*
Dr. Lutz Aschke
Photonic Systems Group

*Starting 7/1/2024*
Dr. Mirko Lehmann
Endress+Hauser Flowtec AG

## Members

Sebastian Bannert
Robert Bosch GmbH

Hanna Böhme
Freiburg Economic Tourism and Trade Fair Agency (FWTM)

Stephanie Busse
DB InfraGO AG

Dr. Mathias Jonas
International Hydrographic Organization

Prof. Dr.-Ing. Katharina Klemt-Albert
RWTH Aachen University, Institute of Construction Management, Digital Engineering and Robotics in Construction

Dr. Fabian Lausen
Federal Ministry of Education and Research

Claus Mayer
Ministry of Economics, Labour and Housing in Baden-Württemberg

Dr. Stefan Raible
Sciosense Germany GmbH

Prof. Dr. Michael Totzeck
Carl Zeiss AG

Prof. Dr. Ulrike Wallrabe
University of Freiburg, Department of Microsystems Engineering IMTEK

# **Investments** 2023

**In 2023, we once again invested in our infrastructure and equipment. This allows us to take full advantage of new technological opportunities to ensure we are able to support our customers with top-class research.**

### Profilometer for measuring surface properties

As part of our research, we manufacture multilayer thin and thick film structures using methods based on microsystem technology. With our recently acquired profilometer, we are able to ensure that the structures are 100 percent consistent with the models and simulations. The contact profilometer measures the geometric characteristics of purposefully structured or technical surfaces. The measurement data provides the basis for the optimized development of layered systems.

## CNC lathe with Y-axis

A universal CNC lathe with Y-axis and interface for powered tools facilitates the manufacturing of sophisticated and complex workpieces in our in-house mechanical workshop. The system spins, drills and mills components in a single cycle and can be individually programmed to create any desired contours. Until now, we have had to transfer spun workpieces into separate milling machines for further processing – at the expense of productivity and accuracy. This combined processing is necessary to meet the increasing demands on components, especially in industrial projects. Optimized machine control using 3D images supports the process.

## Research vehicle as a development platform for measurement systems

We now have a new vehicle available for working on fundamental scientific and technical issues related to the development of mobile mapping vehicles. Our Mercedes Vito is equipped with a roof rack for mounting sensors, a rack inside the vehicle for network infrastructure and power supply, as well as spare batteries to ensure an uninterruptible power supply. A 360° laser scanner, two panoramic cameras and four high-resolution RGB cameras are the basic equipment for accurate surveying of road environments. New hardware components and evaluation software for our measurement systems will be tested under real-life conditions in this mobile laboratory. The vehicle will also be used to generate reference data for research.

*From now on, we will be testing hardware and software components for our mobile mapping vehicles in our own specially equipped survey vehicle.*

# **Professorships** Universities & Universities of applied sciences

**Fraunhofer IPM is represented at the University of Freiburg by three professors and one associate professor. Our close relationship with the university gives us access to the latest basic research. This is the foundation on which we base our project work. The institute also works closely with Furtwangen University (HFU).**

## UNIVERSITY OF FREIBURG

universität freiburg

### Department of Microsystems Engineering – IMTEK

#### Laboratory for Optical Systems

Prof. Dr. Karsten Buse
PD Dr. Ingo Breunig
imtek.de/laboratories/optical-systems

Research foci

- Nonlinear optical materials
- Optical whispering gallery resonators
- Miniature solid-state lasers
- Optical frequency converters
- Integrated optics

#### Laboratory for Gas Sensors

Prof. Dr. Jürgen Wöllenstein
Dr. Katrin Schmitt
imtek.de/laboratories/gassensors

Research foci

- Micro-structured gas sensors
- Microstructured IR emitters for the MIR spectral range
- Laser spectroscopy
- Compact optical gas measuring systems
- Photoacoustics
- Catalytic sensors for flammable gases
- Systems integration

### Department of Sustainable Systems Engineering – INATECH

#### Chair for Monitoring of Large-Scale Structures

Prof. Dr. Alexander Reiterer
Annette Schmitt
inatech.de/alexander-reiterer

Research foci

- Inspection and monitoring of large structures
- Development and implementation of innovative sensor concepts based on laser scanners and cameras
- Data analysis and interpretation with a focus on linkages to influence parameters, causative forces and changes measured
- Development and implementation of complete system chains – from data acquisition to data evaluation


*The Faculty of Engineering of the University of Freiburg is right next door.*

## FURTWANGEN UNIVERSITY

### Faculty of Digital Media

**Professorship of Computer Graphics**
Prof. Christoph Müller
hs-furtwangen.de/en/faculties/digital-media

Research foci

- Real-time 3D visualization for industrial and medical applications
- Interactive visualization solutions for measuring technology
- Photorealism in real-time computer graphics
- Software engineering in 3D computer graphics
- Synthetic training data for AI-based image classification

# **Magazine** Briefly reported

## Our anniversary: 50 years of cutting-edge research


On the occasion of our 50th anniversary in July 2023, we invited representatives from politics, research and industry to join us in celebrating five decades of cutting-edge research at Fraunhofer IPM. During the celebrations, we also gave a glimpse into the future: A panel discussion focused on sustainable and affordable construction and housing – and how measurement technology can help achieve this in the future.

Fraunhofer IPM was founded in 1973 as the Fraunhofer Institute for Physical Space Research IPW. Following a strategic reorientation in the 1980s, the research now focuses on industrial measurement technology. In his opening speech, Director Professor Karsten Buse thanked all employees and partners in research, politics and industry for their support. “Our measurement systems often break world records in terms of speed, accuracy and robustness,” he said, stressing the competitiveness of Fraunhofer IPM’s designs.

*Representatives from research, finance and politics joined Fraunhofer IPM staff to commemorate the institute's research accomplishments over the past 50 years.*

Professor Stefan Rensing, Vice Rector for Research and Innovation at the University of Freiburg, emphasized the close ties between the institute and the university through professorships and successful collaboration in the development of energy-efficient, intelligent and resilient systems. Ulrich von Kirchbach, First Mayor of the city of Freiburg, praised the partnership between the Fraunhofer-Gesellschaft and Freiburg as one of the most important locations of Fraunhofer in Germany. To conclude the celebration, Fraunhofer IPM presented a small exhibition of several measurement technology applications from various departments: a measurement vehicle for 3D data capture of roads and buildings, a system for checking the oiling of metal blanks in pressing plants, a sensor for aerial remote gas detection and the core components of an electrocaloric cooling circuit.

> Fraunhofer IPM is a prime example of how excellent applied research and financial success go hand in hand."
>
> *Dr. Sandra Krey, Executive Vice President of the Fraunhofer-Gesellschaft*

## 10th Gas Sensor Workshop now in person again

The 10th Gas Sensor Workshop at Fraunhofer IPM was another big success: Over 60 participants enjoyed a diverse program and a large exhibition on gas measurement technology.

After the last Gas Sensor Workshop had to be held online during Covid in 2021, this time participants met in person on March 16, 2023. At the institute, they were presented a wide range of topics – from laser spectroscopy for industrial gas analysis and "ship emission monitoring using calibration-free optical telemetry" to trends in compact photoacoustics. Experts from research and industry gave presentations, which were complemented by an exhibition of systems developed by Fraunhofer IPM and its industrial partners, such as InfraTec, Micro-Hybrid, m-u-t and Tycza Industrie-Gase. The next Gas Sensor Workshop is scheduled for March 20, 2025.


GASSENSOR WORKSHOP


*In keeping with the overarching theme of sustainability, the directors of the Freiburg institutes and Professor Hanselka traveled between the institutes by bicycle.*

# New President of the Fraunhofer-Gesellschaft visits Freiburg institutes

At the end of September 2023, Fraunhofer President Professor Holger Hanselka visited Freiburg to learn about the varied sustainability research conducted at the city's five Fraunhofer Institutes. At Fraunhofer IPM, he discovered how we employ measurement technology to make industrial processes more efficient in order to save resources.

Our scientists showed the new Fraunhofer president our mobile mapping vehicles for efficient mapping of urban environments, our extremely fast and accurate measurement technology for reducing rejects in the production of electronic chips, and our novel laser sources that serve as the basis for environmental measurement technology. The president's visit was part of a dialog tour that took him around various Fraunhofer sites to meet employees and external stakeholders.

> "Freiburg is the first stop on my dialog tour, which makes it a special occasion."
>
> *Professor Holger Hanselka, President of the Fraunhofer-Gesellschaft*

*Dr. Daniel Carl explains to Fraunhofer President Hanselka how F-Scanners help save resources by inspecting oil coatings on the production line of a pressing plant.*

*Fraunhofer IPM's Dr. Chiara Lindner (middle) received the Hugo Geiger Prize for her doctoral thesis on quantum sensing. (Other prize winners: Dr. Agnes Bußmann, Fraunhofer EMFT, and Dr. Robert Klas, Fraunhofer IOF)*

# Hugo Geiger Prize for doctoral thesis on quantum sensing

Another prize for Dr. Chiara Lindner: She received the Hugo Geiger Prize 2023 for her excellent applied research doctoral thesis. In 2022, the German Federal Ministry of Education and Research (BMBF) had already honored her work with the Quantum Futur Award.

As part of her doctoral research at Fraunhofer IPM, Lindner developed a quantum Fourier transform spectrometer that allows to quickly and accurately measure the composition of a wide variety of samples using only a millionth of the light intensity of traditional Fourier transform infrared (FTIR) spectrometers. To achieve this, she combined FTIR spectroscopy with quantum technology. This allows to replace the technologically complex and expensive infrared detectors with faster, cheaper and more sensitive silicon detectors, which opens up new applications, such as in the analysis of biological samples.

The Free State of Bavaria together with the Fraunhofer-Gesellschaft awards the Hugo Geiger Prize annually to three young researchers. The jury rates the scientific quality, economic relevance, novelty and interdisciplinarity of the doctoral theses.

*Pioneer in atmospheric science: Dr. Gerhard Schmidtke, a long-time employee of the institute, was presented with the Order of Merit of the State of Baden-Württemberg by the Minister-President of Baden-Württemberg, Winfried Kretschmann.*

# Order of Merit of the State of Baden-Württemberg

How does solar radiation affect the atmosphere and, by extension, the Earth's climate? Dr. Gerhard Schmidtke, a physicist born in Freiburg in 1937, asked himself this question long before climate change became a global issue. For his scientific work, he received the Order of Merit of the State of Baden-Württemberg. The institute's Director Professor Karsten Buse nominated Schmidtke for the award, both in recognition of his outstanding research accomplishments and his tireless social commitment.

For more than 60 years, including during 40 years at Fraunhofer IPM, Schmidtke has been conducting research to better understand the Earth's atmosphere. One of the institute's first employees, Schmidtke was, among other things, the strategic and scientific mind behind SolACES, an experiment conducted on the International Space Station ISS. From 2008 to 2017 – almost a full eleven-year solar cycle – the SolACES instrument provided high-precision data on the intensity of solar radiation and on the highly fluctuating activity of the Sun. The data is used in climate models and helps to understand the relationship between the Sun and our planet. Despite retiring 25 years ago, Schmidtke is still conducting research. His findings on the "radiation imbalance" – the natural greenhouse effect – help to better understand the man-made greenhouse effect and its consequences.


# Open Floor: Meeting new faces, discovering new spaces

Having moved into a new building in 2020, in 2023, Fraunhofer IPM held the first-ever "Open Floor" event series where employees had the opportunity to explore the building, visit different departments and meet colleagues.

Across five Open Floor days, employees were able to spend two hours on one floor to get to know previously unknown parts of the building under the motto "Meeting new faces, discovering new spaces". The series started in February in the basement and then moved one floor up each month. Colleagues presenting their work was not the only entertainment – there was also a puzzle to solve that required employees to explore every nook and cranny of the building. Each Open Floor Day ended with a get-together, with the final day taking participants to the roof terrace with a panoramic view over Freiburg.

# Girls' Day: Discovering the world of measurement technology

Fraunhofer IPM regularly takes part in the annual Girls' Day for pupils in grades 5 through 10. Girl's Day provides insight into jobs in technology, information technology, the trades and the natural sciences – jobs where the share of women is below 40 percent.

In April 2023, all five Fraunhofer institutes in Freiburg participated in Girls' Day. Female pupils were introduced to various research areas – from chemistry to mechanical engineering, from microstructures to space technology and from seismic safety to clean energy. At Fraunhofer IPM they were able to discover the world of measurement technology. And they did not just watch – in each of eight exciting workshops, the girls got hands-on experience: They learned how to build microchips and data networks, draw objects in 3D on a computer and examine insects under an electron microscope.

The Girls' Day campaign is promoted by the German Federal Ministry of Education and Research (BMBF) and by the German Federal Ministry for Family Affairs, Senior Citizens, Women and Youth.

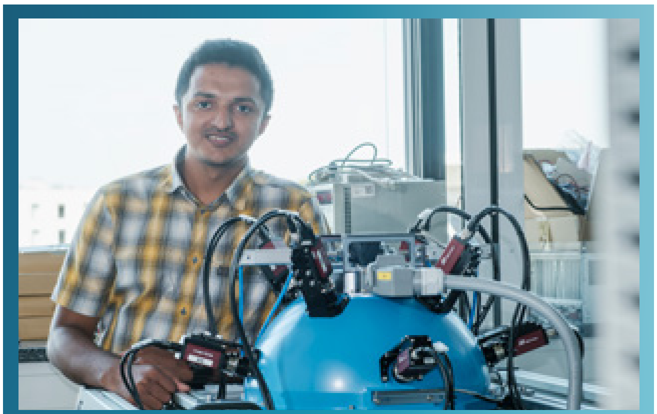
WIR MACHEN MIT!
Girls'Day
Mädchen-Zukunftstag
girls-day.de

# Fraunhofer Science Campus in Freiburg

On July 27 and 28, 2023, the Fraunhofer Science Campus took place in Freiburg. At Fraunhofer IPM, female students and graduates of STEM subjects were given the opportunity to shadow female researchers and learn about different research fields and career options.

Female graduates and students in the areas of science, technology, engineering and mathematics (STEM) from all across Germany participated and explored the Fraunhofer site of Freiburg. They visited all five Fraunhofer institutes for a first-hand look at research in action. In addition to a workshop entitled "From laboratory to production line", information was provided on career opportunities and PhD programs. In a panel discussion, three female Fraunhofer scientists talked about their careers. The Fraunhofer-Gesellschaft regularly hosts the Science Campus at different sites. The goal is to increase the number of women in science and to support junior female scientists.

Science Campus



## Introducing

**Sebin Sunny**
Sebin has been working in production control since 2021. Here, he talks about his background, what he enjoys most and how he ended up in Freiburg.

"I'm originally from India, where I went to school and graduated with a Bachelor's in mechanical engineering. In 2018, I moved to Germany – Jena, to be precise – to earn a Master's degree in Scientific Instrumentation. The focus of my studies was on optics, programming and physics in general. When it came to looking for a suitable job, I suddenly had two good options on the table: An industrial company offered me a great contract, which was even permanent. But in the end, I chose Fraunhofer IPM, mainly because of the people. And because I know that we do research here! I never get bored – there's always something new. I work on camera systems that measure components in free fall, from all sides at the same time. This requires a special image processing system. My main job in this is programming. For example, when we want to optimize certain calculations or when a customer wants to introduce a new defect class. These tasks are always new, which means you always have new problems to solve. I really enjoy that. I can definitely imagine staying here in Freiburg for several more years. I like the people and the city is a wonderful place to live – not too big and not too small. I can easily get around by bike. And when I rent a car, I can buzz over to Switzerland for a hike."

# Quantum magnetometry: Pioneering the future of brain research

**With two events in December 2023, we put the spotlight on optically pumped sensors for quantum magnetometry. One of these events was the Carl-Zeiss-Humboldt Lecture given by Professor Svenja Knappe; the other was a workshop at Fraunhofer IPM.**

*Professor Svenja Knappe showed how quantum sensors could one day offer a window into the brain.*

Measuring brainwaves in 3D is one of the key research areas of Professor Svenja Knappe at the University of Colorado at Boulder in the USA. In 2023, she spent several months as visiting scientist at the University of Freiburg and conducted research at Fraunhofer IPM. This was made possible by her receiving the Carl-Zeiss-Humboldt Research Award 2023, for which she was nominated by the institute's Director, Professor Karsten Buse.

Knappe is an internationally recognized quantum optician who works in the field of magnetic field sensors with optically pumped magnetometers (OPMs). This technology allows neuroscientists to capture brain activity online and non-invasively using magnetic field measurements, which leads to much more accurate results than conventional image-based methods. Knappe's work provides the foundation for unforeseen possibilities in diagnostics, surgery planning and man-machine interaction. The compact OPMs are set to replace today's complex laboratory setups in quantum sensors.

## Carl-Zeiss-Humboldt Lecture: "Will we be able to see thoughts soon?"

On December 11, in connection with her award, Professor Knappe gave a lecture entitled: "Will we soon be able to see thoughts? – Quantum sensor technology for medicine, diagnostics and communication". The lecture was organized by the University of Freiburg in cooperation with Fraunhofer IPM and sponsored by the Carl-Zeiss-Stiftung.

## OPM-MEG workshop with over 60 participants

Optically pumped magnetometers and their application in magnetoencephalography (MEG) were also explored at the first two-day OPM-MEG workshop organized by Fraunhofer IPM together with the University of Freiburg's research center, BrainLinks-BrainTools. On December 12 and 13, around 60 experts met to discuss the potential of OPM technology with a special focus on brain diagnostics. Svenja Knappe also held a keynote on commercializing OPM for neuroscience.

*Integrated into an adjustable helmet, the sensors can be used to examine patients of any age.*

## Background

Each year since 2022, the Humboldt Foundation has been awarding the Carl-Zeiss-Humboldt Research Award to outstanding foreign researchers. The award is aimed at researchers in STEM disciplines who wish to collaborate with specialist colleagues in federal states where the Carl-Zeiss-Stiftung provides sponsorship (Baden-Württemberg, Rhineland-Palatinate and Thuringia). The award is funded by the Carl-Zeiss-Stiftung.

humboldt-foundation.de/en

# Summer school Fraunhofer Photonica: A journey through the world of photonics

Twenty young researchers spent two weeks traveling across Germany to learn more about photonics, light and lasers. The Fraunhofer Photonica summer school is organized by the Fraunhofer Group for Light & Surfaces under the direction of Fraunhofer IPM.

A two-week trip with an in-depth program to five Fraunhofer institutes in four cities – that was the ambitious plan of the Fraunhofer Photonica summer school, which was launched in 2023. One participant's feedback shows that the concept works: "I had two wonderful weeks. The summer school's interesting and informative program allowed me to meet other students and researchers and to learn more about Fraunhofer."

Scientific lectures, tours and independent lab work brought a lot of variety to Fraunhofer Photonica's two-week program. The trip first took the participants from Fraunhofer IPM in Freiburg to Fraunhofer ILT in Aachen. From there, they traveled on to Dresden, where they visited two institutes: Fraunhofer FEP and Fraunhofer IWS. The last stop was Fraunhofer IOF in Jena.

With Fraunhofer Photonica, the organizers were able to get the young researchers excited about photonics and to show them the opportunities and exciting research topics offered by the Fraunhofer institutes. A new edition of Photonica in 2024 will take participants to further Fraunhofer institutes.

*Fraunhofer IPM in Freiburg was the first stop of Fraunhofer Photonica. Participants learned about digital holography as well as career opportunities at Fraunhofer, among other things.*

FRAUNHOFER PHOTONICA

### Fraunhofer Photonica

The Fraunhofer Photonica summer school is organized by the Fraunhofer Group for Light & Surfaces. The goal is to get junior researchers excited about the topics of the Fraunhofer Group and to show them career opportunities at the Fraunhofer-Gesellschaft.

photonica.fraunhofer.de

"The career event at Fraunhofer IPM was most inspiring."

*Fraunhofer Photonica participant*

# Customer interview

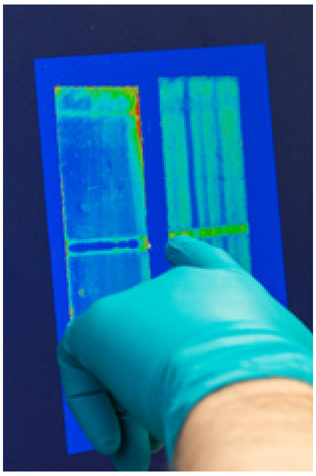
## Plasmatreat GmbH

### "In Research and Development, we focus on things that help our customers get ahead."

**Plasmatreat GmbH has established a global reputation as a custom machine builder focused on the development and production of atmospheric-pressure plasma systems. In this interview, Magnus Buske, Head of R&D, explains how Plasmatreat came to work with Fraunhofer IPM, what has developed from this partnership and what challenges from the world of surface treatment he wants to tackle next.**

**What exactly is your job at Plasmatreat?**
***Magnus Buske:*** As Head of Research and Development, I manage four teams that work on different aspects of plasma technology and plasma processes. We develop not only plasma nozzles and systems, but also customized plasma plants.

**What are your core products and what drives your business?**
We specialize in atmospheric-pressure plasma. Our core business is not only the products themselves, but customized solutions: We help our customers improve the adhesion of adhesives, paints or lacquers on surfaces. The process usually starts with tests in our application engineering department, but it also involves research and development tasks at our technology center.



*"The F-Scanner helps us visualize different levels of contamination and to assess the effectiveness of the plasma treatment," says Magnus Buske.*

**How important is it to collaborate with research institutes in this process?**
Working together with institutes such as Fraunhofer IPM is very important to us. We look for partners with a focus on industry to develop applicable surface treatment solutions. Fraunhofer institutes are perfect for this, because they are able to bridge the gap between basic research and industrial application.

**Where is your company positioned in relation to the competition?**
While there are competitors who also offer plasma technology, only a few take the same solution-based approach as we do. We don't just manufacture the nozzles, generators and transformers needed to power a plasma system, we also design special nozzle heads, for example, to achieve the best results for our customers.

**What role do you think exclusivity plays in the development of new technologies?**
We always strive for a certain level of exclusivity in atmospheric-pressure plasma technology so we can provide our customers with suitable and reliable systems. But we're not trying to be exclusive in every area – just where our technology is used.

**What would you say are essential key technologies?**
Our focus is on plasma pretreatment of surfaces, such as cleaning metal and glass surfaces in preparation for subsequent processes. This is where Fraunhofer IPM's F-Scanner for detecting contamination comes in.


## Plasmatreat GmbH

Plasmatreat is an international leader in the development and manufacture of atmospheric plasma systems for the pretreatment of substrate surfaces. Whether plastic, metal, glass or paper – the industrial use of plasma technology modifies the properties of the surface in favor of the process requirements. The Plasmatreat Group has technology centers in Germany, USA, Canada, China, and Japan. With its worldwide sales and service network, the company is represented in more than 30 countries by subsidiaries and sales partners.

More info: **plasmatreat.com**

**How did you come across our institute?**
An employee from our innovation management group who deals with state-subsidized projects first established contact. While working on an AiF project, in which Fraunhofer IPM was also involved, Mr. Blättermann learned about the possibilities of using plasma to treat surfaces and considered using F-Scanners for detection at Plasmatreat.

**And what happened next?**
The results of our F-Scanner surface contamination detection project were compelling. Especially when it comes to metal components, such as die cast parts for electric motor housings, which need to be glued and sealed, it is important to remove contaminations such as cutting oil. The F-Scanner can detect these residues and show us how severe the contamination is. This allows us to visualize different levels of contamination and assess the effectiveness of plasma treatment.

**Has the F-Scanner helped you achieve your unique position in the market?**
We haven't come across any other provider who can measure surfaces as fast and comprehensively as we can with the F-Scanner. Other companies use similar principles, but none are able to deliver the resolution and speed we need. That made investing into this technology an easy choice – we couldn't find a comparable solution from any other company.

**How do you make a decision with such far-reaching consequences?**
Our groundbreaking decisions are based on a balance between strategic considerations and gut feeling. We evaluate our customer list and potential application cases, and then we decide how promising a specific project seems to us. We don't have a set target for when the investment should pay off: When we recognize a strategic value, we act accordingly.

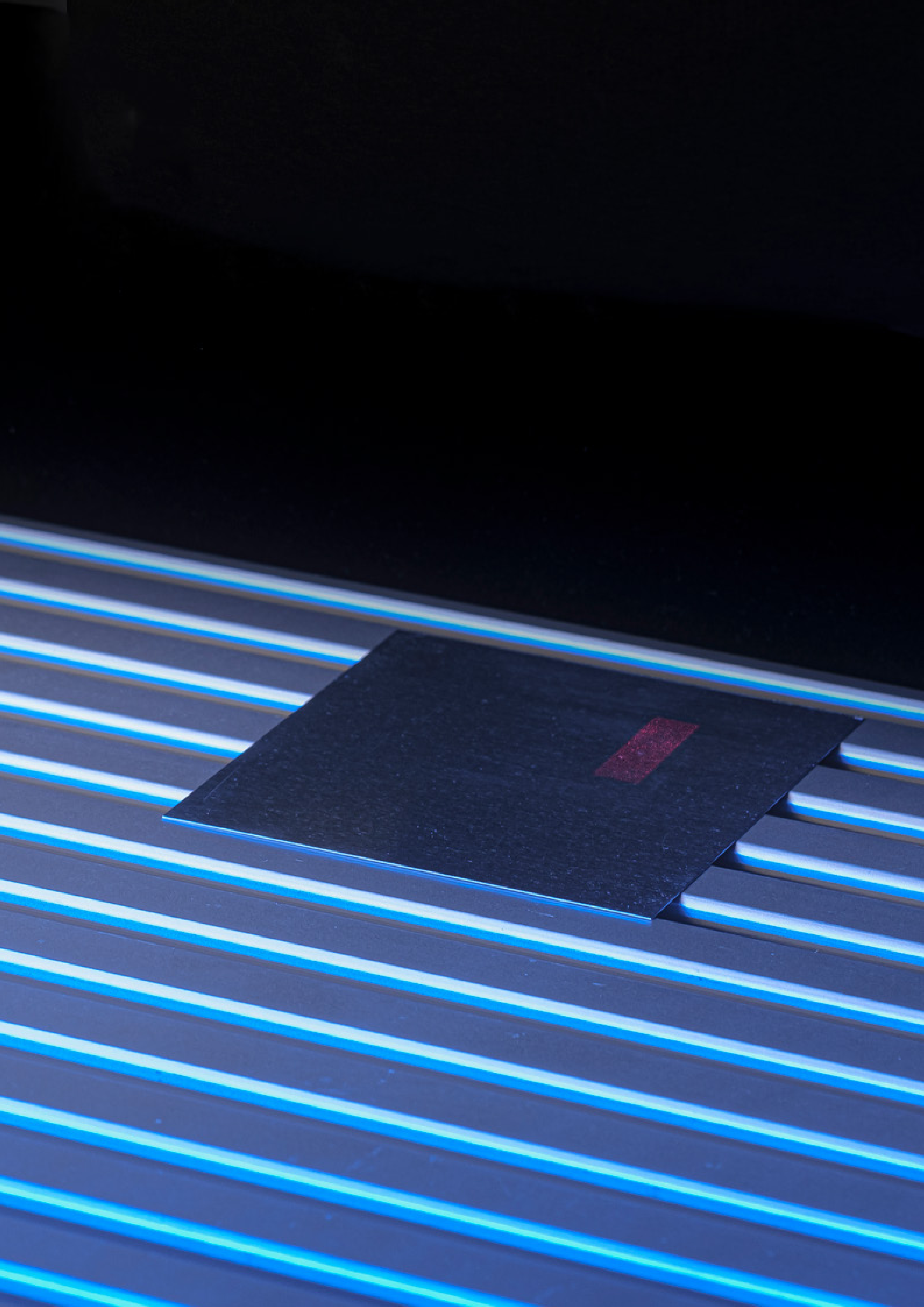
**And last but not least: What are your next challenges?**
Replacing low-pressure with atmospheric-pressure plasma systems is an important trend. We're working on accelerating surface treatment and make it more cost-effective and energy-efficient. In everything we do, we focus on the needs of the industry and strive to replace existing low-pressure processes.

**Thank you very much for talking to us, Mr. Buske!**

*In addition to being a management expert and mechanical engineer, Magnus Buske is also an expert in adhesive technologies. Having previously worked for an adhesive manufacturer, he knows the difference a well-prepared surface can make. He is the Head of Research & Development at Plasmatreat GmbH.*

# Business units

Working for our customers



# **Overview** Production Control

## Measuring as fast as manufacturers produce is our contribution to efficient, controlled production.

Our Production Control business unit develops optical systems and imaging processes for inspecting surfaces and taking precision measurements of complex 3D structures on active production lines. The aim: To ensure processes are controlled and therefore more efficient. Our systems are so fast and so accurate that even the smallest defect or area of contamination can be detected on a high-speed production line and classified in real time. In fact, when combined with (marker-free) individual component tracking and tracing technologies, our optical sensors and measurement systems have the potential to make 100 percent reliable real-time production control a reality – in many cases for the very first time. This assigns them a role as enabling technology for the implementation of modern production strategies against the backdrop of the fourth industrial revolution.

A wide range of methods is used, including digital holography, infrared reflection spectroscopy and fluorescence methods, with fast, low-level image and data processing. They can also be customized to suit different customer use cases, including for forming technology in the automotive sector and for quality assurance in the production of medical devices and electronics.

**Optical sensors and imaging processes**

**Customized systems**

**Data collection and interpretation in real time**

## Our groups and focus areas

### Optical Surface Analytics

- Element analysis in complex multilayer systems
- Analysis of filmic coatings and contaminations
- Detection and classification of particulate contaminations

### Inline Vision Systems

- Surface inspections and dimensional accuracy checks for semi-finished products and components
- Inspection of long products for surface defects and straightness
- Marker-free component identification in production and via mobile app

### Geometric Inline Measurement Systems

- Precision measurement of functional surfaces on active production lines
- 3D measurement of workpieces directly on the machine tool
- Rapid dynamic deformation measurements


"Our fast optical measurement technology systems complement contact measurement technologies."

Dr. Daniel Carl, Head of Department

# **Highlights** Production Control

## Projects · Innovations · Events

*In the future, geothermal plants should not just produce heat, but also lithium. Fraunhofer IPM is developing an optical sensor that should make the method developed at the KIT in Karlsruhe more efficient.*

The LiMo project

### Measurement technology for the efficient lithium extraction in geothermal power plants

Lithium is in high demand all over the world, especially for battery production. The German industry imports lithium despite the fact that it could be extracted locally, for example, from the thermal water of the Upper Rhine Rift and the North German Basin. Geothermal power plants in these areas extract heat from geothermal brine, which also contains lithium, before returning the brine into the ground. The Karlsruhe Institute of Technology (KIT) is using a method that allows geothermal power plants to extract lithium thorough sorption, a method that requires complex laboratory measurements.

"We're now using LIBS technology for liquids at 20 bar and 90 °C. Those are harsh conditions."

*Dr. Carl Basler, Project Manager*

In the LiMo project, which was launched in February 2023, Fraunhofer IPM is developing a sensor based on LIBS (laser-induced breakdown spectroscopy) technology that is expected to make the process more efficient. LIBS is an optical method from the field of material analysis that researchers want to use for inline monitoring of the lithium concentration of geothermal water. This should make it possible to control the sorption and desorption process. The measurement technique is being tested in a geothermal power plant as part of the project. Besides lithium extraction in geothermal power plants, it can also be used in lithium recycling from used batteries.

**LiMo (inline lithium monitoring for the efficient extraction and process control of lithium from geothermal brine and recycling material) project, funded by the Ministry of Economic Affairs, Labor and Tourism of the State of Baden-Württemberg**

The i-skaB project

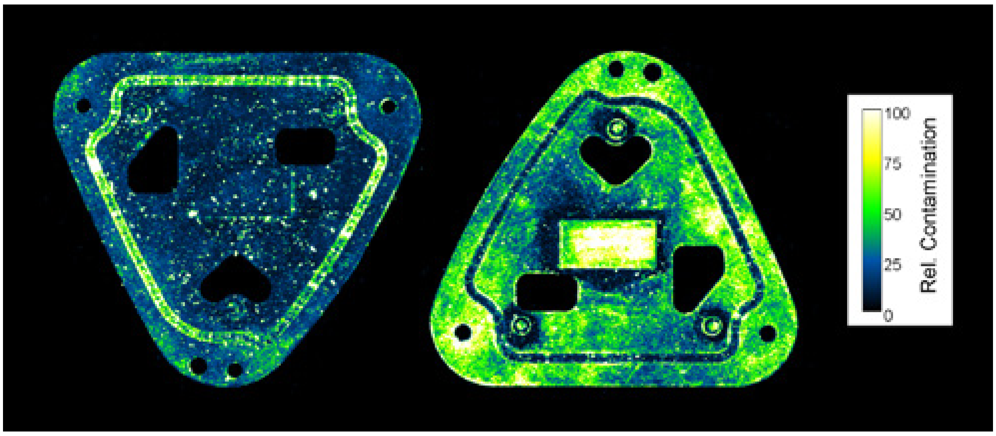
## Fuel cell production of the future

At the beginning of 2023, seven partners from research and industry joined forces in the i-skaB project: The goal of the project is no less than a revolution in fuel cell production. Fraunhofer IPM and its project partners are working on an innovative scalable fuel cell production (i-skaB) that should allow fuel cell stacks to be produced at a rate of 30 seconds instead of the current production rate of a few stacks per day. This requires novel manufacturing technologies that substantially increase the degree of automation. Over the next three years, all key technologies within the production process will be optimized, tested and validated. Quality assurance is another important factor. This is where computer vision and 3D measurement technologies come in.

As part of i-skaB, Fraunhofer IPM is developing methods for rapid optical quality assurance based on innovative computer vision approaches and 3D measurement techniques, such as digital holography. In the medium term, this should increase annual fuel cell production by a factor of 20, from a line output of up to 25,000 fuel cell per year today to over 500,000.

**i-skaB (innovative, scalable fuel cell production) project, sub-project “Development, construction and testing of a digital-holographic measurement system for quality assurance of fuel cell components”, funded by the German Federal Ministry for Digital Affairs and Transport (BMDV); project management agency: Forschungszentrum Jülich**

*The goal of the i-skaB project is to make the highly complex stacking process in fuel cell production much more efficient. Fraunhofer IPM is developing an optical 3D measurement technology for quality assurance.*




*Fluorescent image of a component in false-color imaging: The dark areas are clean, the white areas are extremely contaminated.*

The Qual-Clean | InMoDie projects

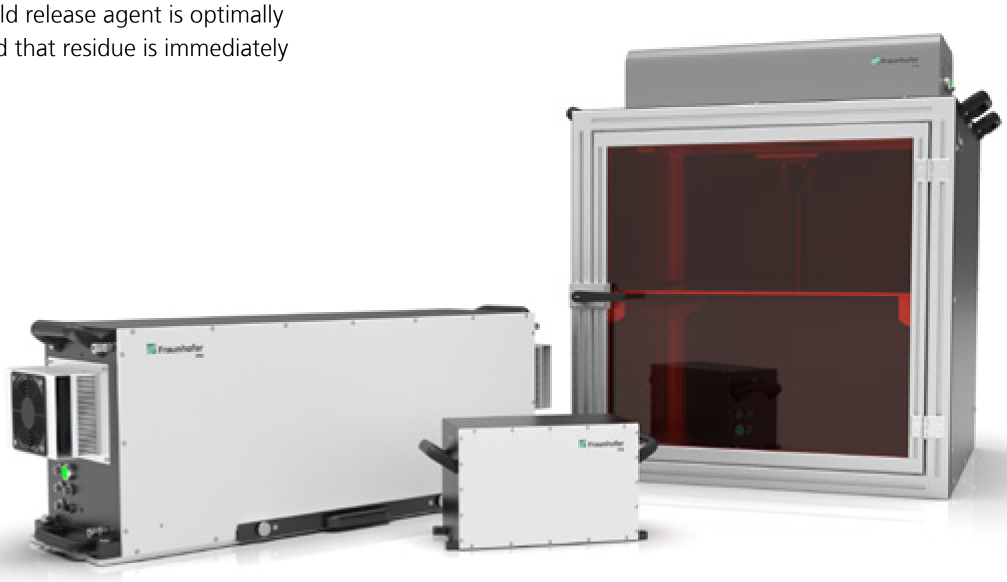
## Detecting contamination with fluorescence

Many modern manufacturing processes depend on a clean component surface. To ensure the quality of adhesion, sealing, coating and vacuum processes, components must be free of organic contaminants. Fraunhofer IPM is developing high-tech fluorescence measurement systems such as the F-Scanner, which assess the cleanliness of entire components inline or in laboratories. The F-Scanner seamlessly checks the cleanliness of surfaces with a combination of laser scanning and highly sensitive laser-induced fluorescent detection.

As part of two joint projects, researchers from the Optical Surface Analytics group are developing additional special systems. The focus of the InMoDie project is cleanliness in the production of lightweight components: A team is developing inspection systems for aluminum/magnesium die casting to ensure that the required mold release agent is optimally applied during the process, and that residue is immediately detected at the end of the process. In the Qual-Clean project, Fraunhofer IPM is developing a quality assurance system that can be integrated into the cleaning process, which guarantees and documents the cleaning of critical components. To achieve this, the F-Scanner technology is combined with the $CO_2$ snow-jet cleaning technology by industrial partner acp systems AG.

**InMoDie (Development of an inline measurement technique for spatially resolved detection of filmic contaminants on component surfaces and the support of release agent application in die casting) project, funded by the German Federal Ministry for Economic Affairs and Climate Action (BMWK) as part of the Technology Transfer Program Lightweight Construction**

**Qual-Clean (Targeted local cleaning and quality control of critical component areas in production) project, funded by the Ministry of Economic Affairs, Labor and Tourism Baden-Württemberg as part of the Invest BW program**



*The F-Scanner product line: F-Scanner 1D, F-Scanner 1Dmini, F-Scanner 2D*

*Novel laser light sources help provide an economically viable solution for demanding measuring tasks, such as those involved in the production of microchips.*

The MultiLambdaChip project

## New lasers for digital holography

Modern optical measurement techniques such as digital holography enable inline quality assurance. However, until now, the size and cost of the light sources have prevented these measurement techniques from becoming widely established. With the MultiLambdaChip research project launched in 2023, Fraunhofer IPM wants to tackle this issue and develop highly integrated, cost-effective laser light sources for use in digital holography, working in collaboration with HÜBNER Photonics, Carl Zeiss AG, cyberTECHNOLOGIES GmbH and the Laboratory for Optical Systems at the University of Freiburg.

A key element of the new multiwavelength laser light source is a novel photonic circuit based on lithium niobate. The idea is to manipulate and convert the 1550 nm light of an inexpensive type of laser diode normally used in telecommunications, and enable it to take high-precision measurements in the visible spectral range. This cost-effective light source will make the use of holographic measurement systems cost-efficient for many new tasks in modern production. High-tech industries rely on many critical components with low tolerances being produced at high cycle rates. The production of microchips or high-performance electronics for e-mobility or renewable energy applications are good examples. Digital holography can, in principle, ensure reliable quality control in these scenarios.

The MultiLambdaChip project also sets out to prove the operational capability of the new laser light source used in combination with holographic measurement systems for two industrial applications. Firstly, a novel holographic line sensor is designed to enable quality assurance during bake-out of microchips for the first time. Secondly, a holographic sensor system capable of taking comprehensive measurements is due to be integrated into a multi-axis handling system to allow the dimensional accuracy of ceramic components to be 100 percent controlled. Achieving these objectives will, for the first time, make it possible to take high-precision in-line 3D measurements that could previously only be carried out in special measuring rooms.

**MultiLambdaChip (Integrated optical multiwavelength laser system for holographic 3D surface metrology in industrial quality assurance) project, funded by the German Federal Ministry of Education and Research (BMBF)**

"Novel laser sources will make digital holography even more profitable."

*Dr. Alexander Bertz, Group Manager*

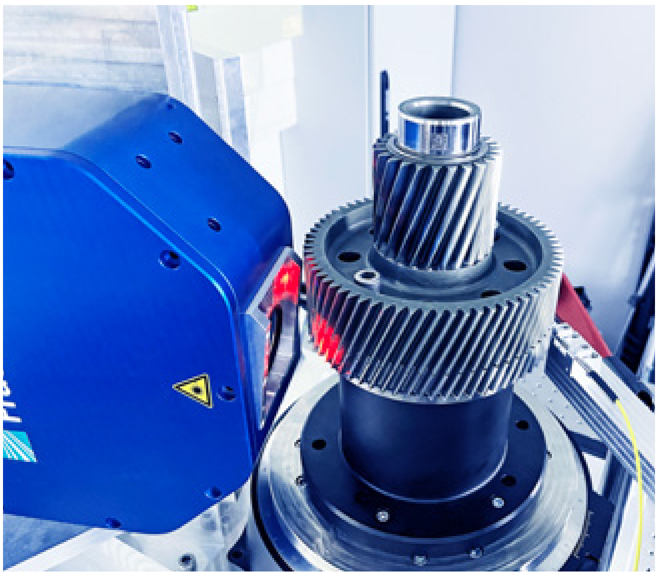
The HoloMotion project

## Digital holography in motion

Until recently, performing digital holographic measurements on moving samples was deemed impossible. In its HoloMotion research project, Fraunhofer IPM has managed to make the impossible possible, though: For the first time, components can be interferometrically measured in motion with high accuracy. Researchers have demonstrated that digital holographic measurements are possible at a speed well above 10 mm/s. Together with the industrial companies FRENCO GmbH and ZF Friedrichshafen AG, they designed and tested a demonstrator system for optical gear measurement in a production environment. This is a major accomplishment, because interferometric gear measurement is very challenging due to the high tilt angle and low tolerance. As a purely optical method, digital holography has a huge advantage over the established tactile gear measurement: It is capable of areal flank measurement in one-second intervals. In the six-year project, which was completed in early 2023, researchers were able to significantly advance the technology of digital multi-wavelength holography, and to perform optical gear measurements in industrial environments for the first time.

**HoloMotion (Dynamic holographic measurement technique for capturing metallic freeform surfaces) project, funded by the German Federal Ministry of Education and Research (BMBF)**

*The digital holographic measurement of gears in industrial environments is possible. Fraunhofer IPM was able to demonstrate this in the HoloMotion project.*



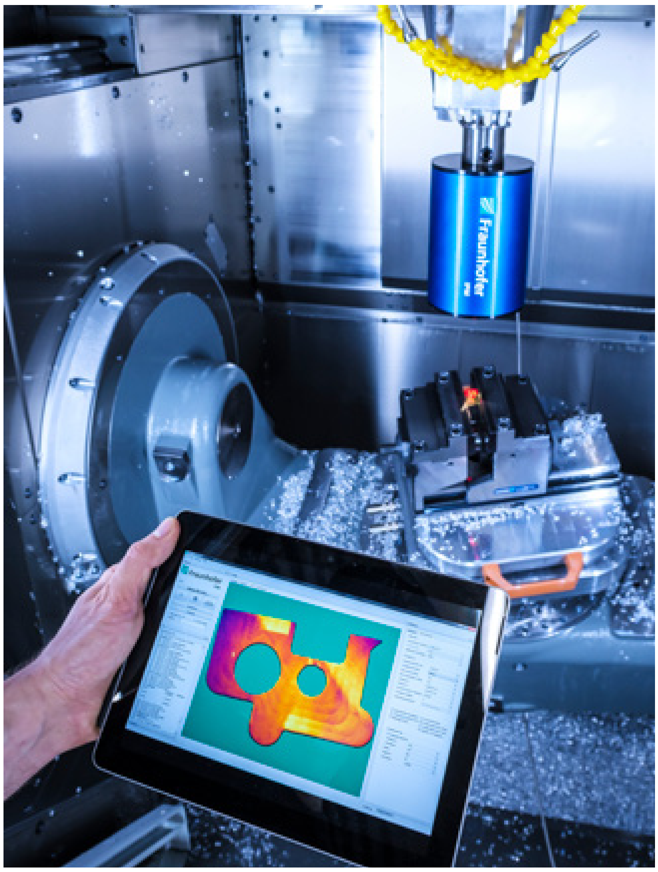
Publication

## Digital holography in a machine tool vs. coordinate measuring machine in a laboratory

Machine tools play a central role in industrial production. The ever-increasing level of automation has turned them into high-precision mechatronic systems, which makes the accurate inspection of geometric quality characteristics increasingly important. Tactile random inspection of components with a coordinate measuring machine is state-of-the art. While it is very accurate, it is also very time-consuming. Researchers at Fraunhofer IPM have now succeeded in performing a comparably accurate quality control of many characteristics directly in the machine tool.

To this end, they developed a highly compact holographic sensor, which can be moved like a tool over a component in the machine tool. The HoloTop NX sensor has a measurement field of 12.5 × 12.5 $mm^2$ and a lateral resolution of about nine million pixels. The comparison of the data set of digital holographic measurements in machine tools with the tactile

*The digital-holographic HoloTop NX sensor integrated into a machine tool provided equally accurate 3D surface measurement data as a tactile coordinate measuring machine.*



*Track & Trace Fingerprint Flex on a robotic arm: The system identifies components and can be used anywhere in the production environment.*

measurements of a cutting-edge coordinate measuring machine (CMM) left the team itself somewhat surprised: The Root Mean Square Error between the two data sets is less than 0.4 µm. The team was able to demonstrate that digital holography is perfectly suited for fast and accurate 3D surface height measurements in machine tools, and capable of providing similarly accurate data as the tactile measurements of a CMM – only at a much higher speed. In the future, the team plans to investigate the reproducibility of an entire series of measurements with both systems. This research work was financed by Carl Zeiss AG. The tactile reference measurements were carried out by toolcraft AG.

**Scientific publication: »Digital holography in a machine tool: measuring large-scale objects with micron accuracy«**

Marker-free component identification

## New: Track & Trace Fingerprint Flex

The Inline Vision Systems team has added a new system for flexible application to the Track & Trace Fingerprint system family: With the cordless Track & Trace Fingerprint Flex, components can be reliably identified on a random sample basis. Unlike Track & Trace Fingerprint Inline, which is integrated into the production line, the battery-driven Flex system can be used anywhere in the production environment. Mounted on a robotic arm, Track & Trace Fingerprint Flex identifies components at various points of the production process: As a hand-held device, it can identify parts in assembly, logistics or quality assurance and retrieve product history data. Control and data transfer are carried out with a laptop, tablet or computer via Wi-Fi. The system is suited for identifying components with various geometries, surfaces and materials.

Like all Track & Trace Fingerprint systems, the Flex system also uses the surface microstructure of the components for marker-free identification. The fingerprint code, a characteristic bit sequence, is calculated based on the specific structural patterns in an image and their position in relation to each other. The code is assigned to an object ID and stored in a database. When the component is identified at a later point, this process is repeated at the same location on the component, and the new fingerprint code is matched with the one stored in the database. Individual components can be reliably identified among millions of components of the same type – without additional markers.

The DiGeBaSt project

## Reliable proof of origin: Marker-free tracing of logs

Where does this log come from? The EU requires the timber industry to answer this question reliably at all times, not least in order to curb the growing illegal timber trade. However, the usual numbering tags, RFID codes or color markings do not guarantee a reliable proof of origin.

As part of the DiGeBaSt project, Fraunhofer IPM has adapted its Track & Trace Fingerprint method – originally designed for tracing industrial components – to recognize logs. The camera-based technology uses the individual surface texture of cut surfaces as a fingerprint for identification. High-resolution images of the cut surfaces are translated into a simple bit sequence, the fingerprint code. To identify it later, another camera image of the same cut surface is taken and matched with the code. Besides tamper-proof traceability, this reliable identification method also enables the end-to-end digitalization of supply chains in the timber industry.

Three camera systems were developed for a forest environment: one system is integrated into the forest harvester, one is used in the sawmill and another as a hand-held system. The material properties of wood and the harsh environmental conditions posed significant challenges for the technology. However, in a field study with 65 trunk sections, the team at Fraunhofer IPM was able to achieve high recognition rates: Trunk sections scanned at the forest harvester and at the timber collection point were correctly identified at the sawmill with 100 percent accuracy while sections scanned at the forest harvester were recognized with a 98.5 percent accuracy at the timber collection point.

**DiGeBaSt (digitalization of felled logs) project, funded by the Federal Ministry of Education and Research as part of the "Digital GreenTech" funding program**

The hotCAM project

## Track & Trace Fingerprint: Software facilitates training of new component types

Almost all surfaces have a microstructure that is as unique as a fingerprint. The Track & Trace Fingerprint method takes advantage of this fact for marker-free tracing: A camera captures the surface of components in high resolution. The fingerprint code, a characteristic bit sequence, is calculated based on the specific structural patterns in an image and their position in relation to each other. The components can be identified again later when the process is repeated. To ensure they are recognized, the components always have to be scanned in the exact same position. This used to require a component-specific image preprocessing that recognizes the fingerprint area in the captured images. A software that was developed as part of the hotCAM project now facilitates the training of new component types.

With FPPartPlaner, the system can be easily trained to recognize new component types using an intuitive user interface – no programming skills are required. This is done by uploading the component's CAD data in DXF format. The user then defines the fingerprint area based on this CAD data. On this basis, a correlation algorithm can recognize the component's position and automatically determine the fingerprint area. The project research team tested the software in a hot rolling mill. The steel profiles processed in the mill come in different shapes that may change during the process due to fluctuating temperatures. In addition, they are not always placed in the exact same position. However, the software was still able to help detect the fingerprint area of around 300 steel profiles and reliably identify them.

**HotCAM (reading system for marker-free fingerprint recognition of semi-finished products over 1200 °C under very harsh environmental conditions) project, funded by the Fraunhofer-Gesellschaft (SME project)**

*The Track & Trace Fingerprint system captures the cut surfaces of tree trunks on the forest harvester.*

The DigiBattPro 4.0 project – BMBF

## Marker-free position measurement of sheeting

In the production of sheeting such as flat steel, steel strapping or metal foils, sometimes an entire coil – which means several tons of steel – has to be discarded because of a single defect. The risk of a defective section being integrated into a final product is too great. From a financial and ecological perspective, it would make more sense to discard only the defective section of a coil. This would require measurement and process data to be matched to the exact position on the coil, which has not been achieved yet. In some cases, continuous laser engravings or colored markings have been used, but depending on the product, this can compromise the surface or interfere with downstream processing. Determining the position with a rotary encoder is not accurate enough. Furthermore, the position cannot be determined anymore once the coil has been cut into sections. The solution would be an absolute position measurement on the coil, which would have the added advantage of allowing sections to be traced further down the line.

Fraunhofer IPM and Fraunhofer IPA jointly investigated whether the Track & Trace Fingerprint method for marker-free component identification could be used for high-precision position measurement using electrode foil as an example. After being plated, the 30 µm thin copper/aluminum foils are cut into electrodes. Before they are cut into sections, cameras capture the tab area, which is only a few square millimeters wide, on the edge of an electrode strip. In this case, two times four cameras were installed above the conveyor belt of a pilot system, which – assigned to four electrode strips – captured and later identified the fingerprint area at a feed rate of 25 m per minute. The team was able to successfully identify electrode sections based on the surface microstructure without any ambiguity, matching the process data of a position on an electrode foil with an accuracy of 100 micrometers. The team is working on adapting the method to other applications in metal blank processing and for other materials, such as paper. This should lay the groundwork for creating digital twins in the production and processing of sheeting.

**DigiBattPro 4.0 – BMBF (Digitalization solutions and material development for battery production) project, funded by the German Federal Ministry of Education and Research (BMBF)**

*Reliable tracing of sections: In the production of sheeting, process data can be linked to a specific section of a coil with Track & Trace Fingerprint technology.*

"We will be able to link the process data with a specific position on a coil."

*Dr. Tobias Schmid-Schirling, Group Manager*

The ARIMA HT project

## Real-time image correlation for uniaxial and biaxial crack propagation tests

Centrifugal forces, pressure, temperature changes – mechanical components, such as in aircraft, turbomachinery or power plants, are subjected to extreme conditions. Sooner or later, cracks start to form. Crack propagation tests reveal the propagation behavior and speed of cracks and provide an experimental data basis for component engineering and for assessing the remaining service life of components.

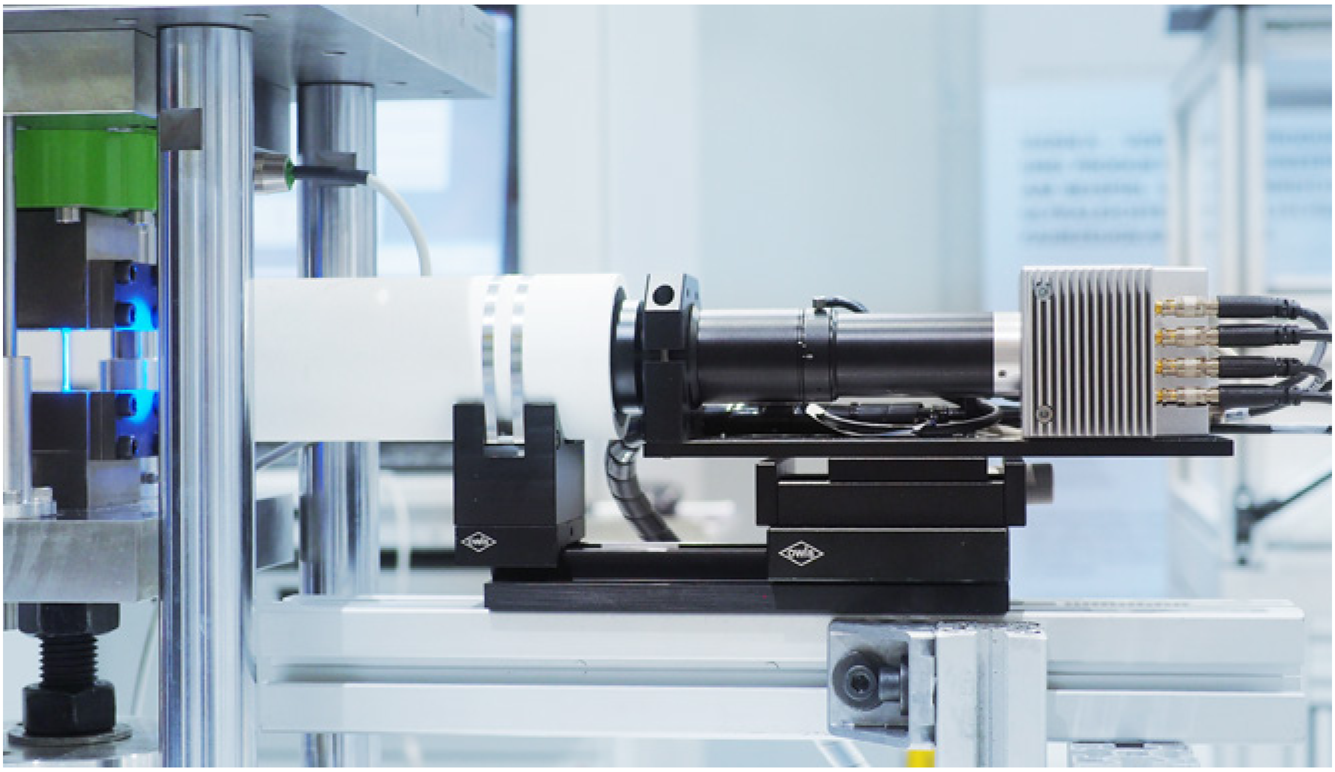
In the ARIMA research project, Fraunhofer IPM has developed an innovative measurement technology for uniaxial and biaxial crack propagation tests in cooperation with the Institute of Materials Science (IfW) of the Technical University of Darmstadt. The technology is based on the principle of digital image correlation (DIC) and captures integral strain – as mechanical extensometers do – as well as entire strain fields, and evaluates them in real time. Since this method captures several variables with a single sensor, it allows for a simplified test procedure and a comparison with finite element simulations, providing experimental validation.

DIC is an image processing method widely used in materials testing for measuring strains and shifts under stress with subpixel precision. The high computational load of conventional processors makes this method too slow for crack propagation tests. For this reason, our researchers rely on a combination of fast cameras and graphics processor units (GPU): Modern cameras capture more than 1500 images per second; GPUs correlate up to 74,000 DIC measuring points per second. Another advantage is that metallic samples do not need to be prepared with speckle varnish, because the high-resolution cameras can resolve their microstructure without additional markings. This marker-free measurement makes the detection of crack tips easier while avoiding changes in emissivity of the material.

In 2023, the follow-up project ARIMA HT was launched together with IfW. The goal is to qualify the measurement technology for crack propagation tests under high temperatures.

**ARIMA HT (Assurance, development and application of evaluation methods of crack behavior under multiaxial high-temperature stress situations close to the components) project, funded by the Federal Ministry for Economic Affairs and Climate Action and the German Federation of Industrial Research Associations (AiF)**

*Optical over mechanical: Strain measurements with a camera sensor allow for a simple test setup, as seen here at Fraunhofer LBF, and provide more measurement parameters than mechanical extensometers.*



# **Production Control |** Trade Fairs & Events

## BAU

April 17–22, 2023
Stand of the Fraunhofer Building Innovation Alliance

We showcased an exhibit on marker-free traceability of components using Track & Trace Fingerprint and presented solutions on the topic of "Digital Process Chain and Recycling".

## CONTROL

March 09–12, 2023
Fraunhofer Business Unit VISION

The Optical Surface Analysis team presented the F-Scanner 1Dmini, a fluorescence scanner for testing the surface cleanliness of components in production. The Inline Vision Systems were represented with the Inspect 360 HR inspection system for high-precision measurement of geometry and surface quality.

## parts2clean

September 26–28, 2023
Fraunhofer Business Area Cleaning

Our topic was cleanliness control in the line based on fluorescence measurement technology. The F-Scanner 1D mini and the F-Camera mini were exhibited.

## Technology Day Vision

October 25–26, 2023

Fraunhofer IPM was represented at the exhibition with a robot-assisted F-Scanner for cleanliness and coating inspection and the Track&Trace fingerprint technology for marker-free tracking of components.

## Blechexpo

November 07–10, 2023
EFB joint stand

We displayed an imaging optical inline measuring system that measures the oiling of sheet metal in the production cycle over the entire surface. We also presented a process for the mark-free tracing of endless sheets.

## Fairs & events in 2024

**Joining in Car Body Engineering**
February 27–28, 2024

**HMI**
April 22–26, 2024

**Control**
April 23–26, 2024

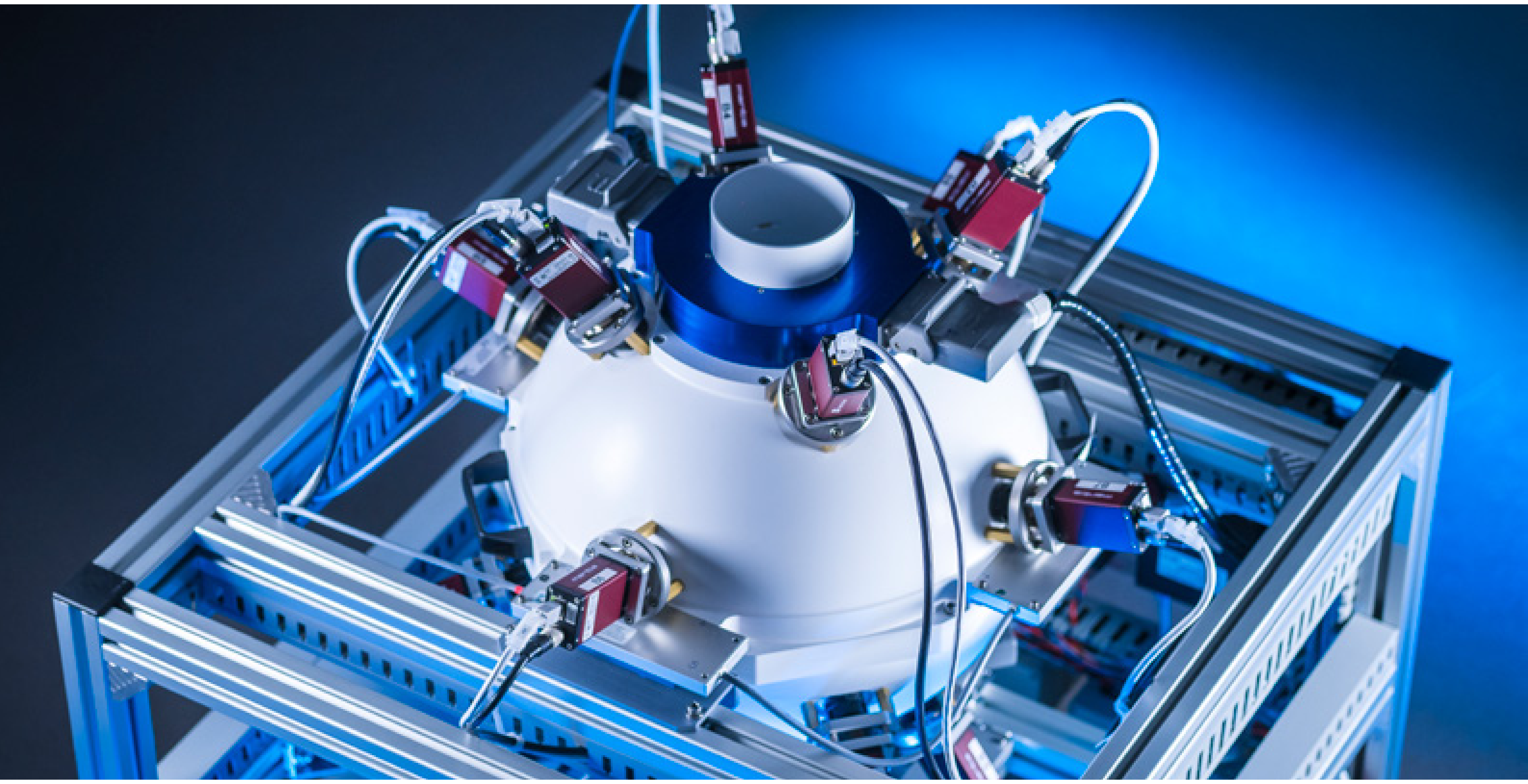
**Surface Technology**
June 04–06, 2024

**EuroBLECH**
October 07–10, 2024

**Quantum Effects**
October 08–09, 2024

# **Focus** Inline quality control

## Efficient component testing: Inspection in free fall



*The Inspect-360° HR free-fall inspection system is particularly suitable for inspecting small parts up to 3 cm in length. Thanks to a pixel resolution of 15 µm, the system detects even the slightest surface defects.*

Today's formers, die cutters and injection molders must become ever more accurate: The manufacturing tolerances are often only a few hundredths of a millimeter. Even a random sample quality control can soon become expensive – thorough documentation with conventional test methods is simply not profitable. In the last few years, Fraunhofer IPM has worked hard on making inline component inspection more efficient and inexpensive. The key approach is free fall inspection.

Inspecting components in free fall has several benefits: It does not require cumbersome positioning of the component, and multiple high-performance cameras and intelligent software allow the entire component surface to be captured in one go, which saves time and money. The free-fall inspection systems from our Inspect-360° series examine the geometrical dimensional accuracy and texture of differently shaped semi-finished products inline – with a lateral detail resolution of down to 15 µm. Other system variants can perform special surface inspections for cleanliness and coating quality. What's convenient for users: All desired inspection methods can be customized and integrated into a single system – and all necessary quality data is recorded in a single inspection process.

## Simple line integration

The components are transported individually into a hollow sphere for inspection via a conveyor belt. They fall through the sphere and are captured by up to 27 cameras from all angles simultaneously – sometimes, the cameras even take multiple photos. Diffuse light is used to ensure the components are captured without cast shadows and reflections. This also works for shiny or oily surfaces. The only requirement: The components must pass through the sample volume one at a time, no matter which way they are facing.

As part of the line integration, all CAD models of the component types to be tested are presented to the inspection system to ensure they can be recognized. There are now two options when it comes to testing geometrical dimensional accuracy: One entails using a global threshold value to determine how large the maximum permissible contour deviation should be in relation to the CAD model. The other uses two additional CAD models per component type to determine the upper and lower tolerance limit on a local level.

## Surface texture recognition using AI

AI-based anomaly detection is used to inspect the surface texture of the components. Only compliant parts are used to train the neural network, removing the need for the often time-consuming search for defective parts. This method detects issues such as scratches, cracks and deep dents. The defects can be classified downstream by means of additional image processing.

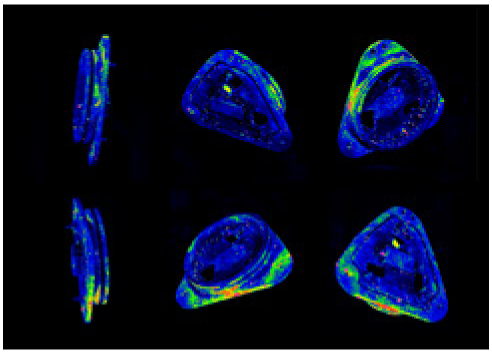
When being used to check quantitative cleanliness or inspect coating quality, the Inspect-360° system can also be equipped with a UV light source that stimulates organic substances on the surface into a state of fluorescence, thereby making them visible. Even microcracks that are not visible to the naked eye can be detected by UV lighting if a fluorescent marker is used. In conjunction with the recorded geometric characteristics, it is therefore possible to automate defect recognition and reliably differentiate between defects and pseudo readings.

## Evaluation with up to 5 Hz

Inspect-360° free-fall systems are capable of inspecting parts directly in the production line and filtering out defective parts at one-second intervals. This enables direct intervention and feedback into the process. Alongside quality control, the systems can also monitor the set-up and warm-up phases of the process. The systems therefore increase overall production efficiency by significantly shortening these phases and reducing waste. If even higher cycle rates are required, an Inspect-360° system can be configured in such a way that allows several inspection orders to be processed in parallel on different PCs, enabling the system to be used for cycle frequencies of up to 5 Hz or 300 components per minute during production.

"Expensive handling is often the main spanner in the works when it comes to economical quality control."

*Dr. Daniel Carl, Head of Department*



*Quantitative cleanliness testing is also possible in free fall: This requires an additional UV light source that stimulates organic substances into a state of fluorescence.*

# **Overview** Object and Shape Detection

## The automation of 3D data collection and processing is our contribution to the digitalization of our environment.

Our Object and Shape Detection business unit is focusing on the entire process chain for the automated mapping, referencing, analysis and visualization of the geometry and position of infrastructural objects. We develop measurement systems, mainly LiDAR systems, and custom lighting and camera systems for mapping objects and shapes three-dimensionally with extreme speed and precision – mostly from moving platforms. Typical measuring ranges are between a few centimeters to hundreds of meters.

Measured data is evaluated in a fully automated process and analyzed by specially developed software. To this end, we employ techniques from the field of artificial intelligence (AI), such as deep learning. Data that is processed and visualized for specific applications provides a sound basis for planning, which is particularly important where infrastructure is concerned, for instance.

**Fast, precise and robust sensors**

**Miniaturized measurement systems**

**Data analysis software**

## Our groups and focus areas

### Mobile Terrestrial Scanning

- Systems for mobile mapping vehicles
- Systems for regularly circulating vehicles
- Sensor and data fusion for complete systems

### Mobile Railway Measurement Techniques

- Systems for measurement trains
- Systems for regular trains
- Sensor and data fusion for complete systems

### Airborne and Underwater Scanning

- Systems for unmanned aerial vehicles
- Systems for underwater applications
- Signal analysis for demanding measurement environments

### Autonomous Measurement Robotics

- Adaptation of sensors to be applied in robotic systems
- Integration of complete robotic systems
- Realization of cooperative systems

### 3D Geodata Analytics

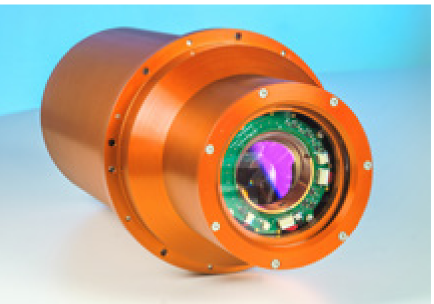
- AI-based semantic segmentation of 2D and 3D data
- Real-time visualization of spatial data
- Creation of synthetic measurement data
- Platform-independent systems

> We can use LiDAR under water, too. That's why we have developed multispectral laser scanners."

Professor Alexander Reiterer, Head of Department

# **Highlights** Object and Shape Detection

## Projects • Innovations • Events



*The Underwater LiDAR System's sensitive technology is cased in a pressure-resistant housing, enabling the sensor to dive to depths of several hundred meters.*

Maritime geomapping

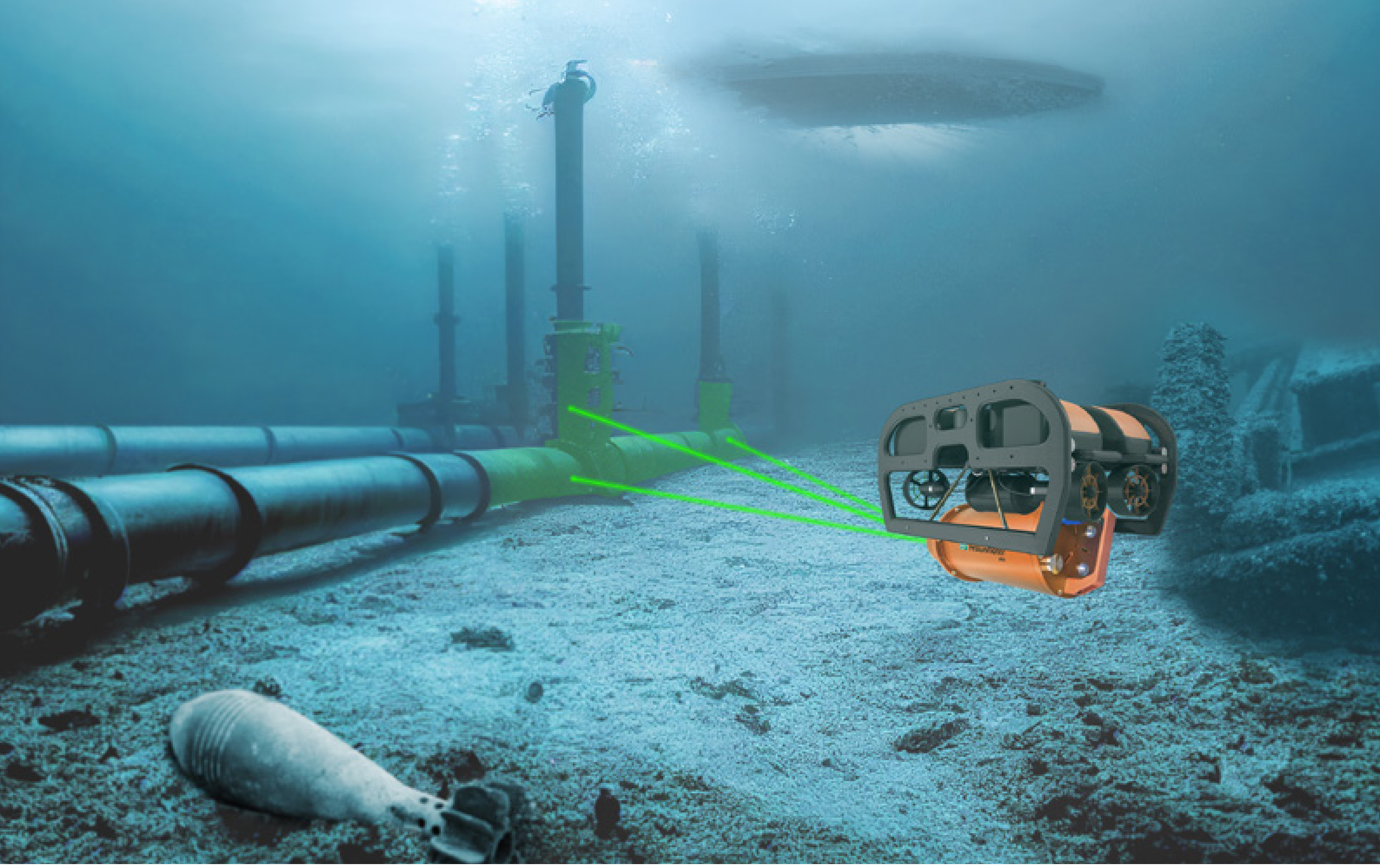
### Finland relies on underwater LiDAR by Fraunhofer IPM

The Finnish Geospatial Research Institute is going to use the Underwater LiDAR System ULi and the Airborne Bathymetric Laser Scanner ABS to survey maritime areas in the future. The renowned research institute expects these two systems combined to deliver high-quality maritime geodata and more efficient field measurements, during applications such as monitoring the status of undersea infrastructure or conducting topographic surveys of coastal waters. Until now, cameras and sonar systems have been used as standard. The widespread use of LiDAR systems for taking submarine measurements has so far been thwarted primarily by the strong light attenuation through the medium of water, as well as by suspended particles found in water.

Our ULi and ABS LiDAR systems make it possible to take 3D measurements under water and bathymetric measurements from the air with unprecedented precision. The ULi sensor detects objects underwater with millimeter precision using the pulsed time-of-flight method, making it up to ten times more accurate than sonar systems, for example. The sensor can take measurements from a ship or underwater vehicle, both from a static position and in motion, and deliver an accurate 3D model of undersea infrastructure such as offshore wind turbines, pipelines and submarine cables. The ABS uses two lasers with different wavelengths to topographically survey coastal areas at up to twice the Secchi depth with millimeter precision. The system's low weight is a major advantage: Weighing less than three kilograms, the sensor is currently the lightest bathymetric LiDAR system in this performance class and can therefore be used on standard drones with no need for a specific flight permit.

> Here we have a powerful tool to map coastlines and survey objects in 3D at great depths."

*Professor Juha Hyyppä, Director Remote Sensing and Photogrammetry at the Finnish Geospatial Research Institute*



*LiDAR sensors can inspect undersea infrastructure efficiently and with millimeter precision. (Photo montage)*

The CoLiBri project

## Sensor platform for inspecting undersea infrastructure

The clue is in the project name: The collaborative sensor platform, which has been under development as part of the CoLiBri project since June 2023 by a team of Fraunhofer IPM together with the Finnish Geospatial Research Institute FGI and partners from the Sustainability Center Freiburg (LZN), is set to be particularly lightweight and compact. This is expected to enable both high-resolution mapping of coastal waters and the inspection of undersea infrastructure.

Two multispectral pulsed LiDAR systems are integrated into the platform: an ultra-lightweight bathymetric scanner for use on unmanned drones and a compact 3D scanner for use on remote-controlled underwater vehicles (ROVs) and ships. Both scanners will use a new LiDAR module that is being developed, consisting of lasers, optics and new solutions for signal processing, position measurement and georeferencing.

As well as the hardware, data evaluation is another focal point of the research. The LiDAR systems record five giga-samples per second. The data is examined using a full waveform analysis. Researchers are developing a software to merge and analyze the data from both scanners, which will also resolve interference caused by the salinity and temperature of the water. The project's flexible technical basis and uniform process combined is set to make maritime geomapping simpler, more cost-effective and more efficient than ever before.

**CoLiBri (Collaborative LiDAR to Monitor Infrastructure in the Water and at the Shoreline) project, funded by the Fraunhofer-Gesellschaft (IMPULS project)**

*Finnish researchers test the ultra-lightweight bathymetry laser scanner.*

New mobile mapping vehicle

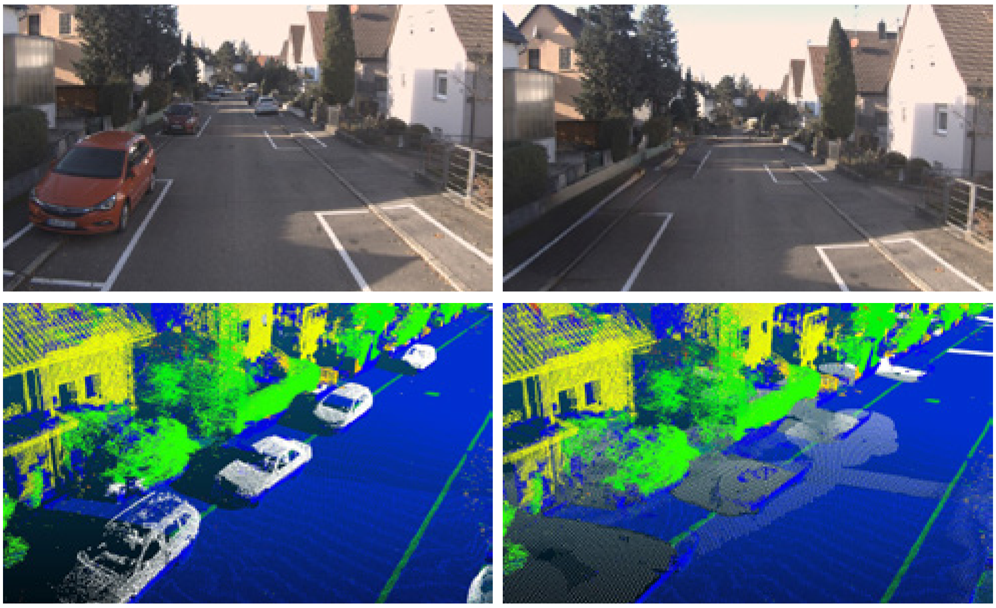
## Universal survey vehicle for municipal construction planning

Sound measurement data is the be-all and end-all when it comes to evaluating road infrastructure and planning municipal construction measures efficiently. Fraunhofer IPM has developed a survey vehicle for the construction company HOCHTIEF that is equipped to carry out a wide range of measuring tasks: High-resolution cameras and laser scanners measure longitudinal and transverse evenness as well as surface characteristics of the road surface. A pyrometer also records the road surface temperature. The measurement system features a built-in inertial measuring unit and a GNSS module to record position and orientation. The operating software enables live monitoring to allow the sensors to be monitored and the data quality to be tested during travel. In future, the vehicle is set to be capable of condition assessment and evaluation in accordance with official Federal Highway Research Institute (BASt) guidelines.

In addition to road status monitoring, the survey vehicle is also fitted with a Fraunhofer IPM clearance profile laser scanner and four cameras to capture the street environment. Post-processing software processes the measurement data to form a georeferenced point cloud.

HOCHTIEF subsidiary company Edgital uses the universal survey vehicle to take field measurements on behalf of municipalities, thereby providing the very first overall solution for the status evaluation, planning, management and documentation of construction projects. The vehicle is also expected to support Germany's fiber-optic expansion in future: The measurement data recorded meets Deutsche Telekom's requirements for planning the FTTH (Fibre-to-the-Home) expansion.


*Highly sophisticated measurement technology: A universal vehicle records the state of the road surface while capturing the street environment at the same time.*



*Car-free city center: Cars are identified in the camera images (top row) using automated object recognition, before generative AI fills in the image areas to create the basis for "complete" planning maps. By merging the camera images and point clouds, it is possible to eliminate the car areas in the 3D point cloud (bottom row) and interpolate the missing street surfaces.*

Deutsche Telekom

## New software release optimizes route planning for the fiber-optic expansion

Parked cars are not just a nuisance in real life. They can also cause problems when surveying streets using cameras and LiDAR sensors: Important information is missing in places where cars appear in camera images and point clouds, such as the condition of the road surface underneath or the sidewalk surface behind the vehicle. These data gaps are a problem for the planning algorithms, as construction planning must be accurate to within a few meters in order to ensure the optimum use of construction vehicles, for example.

Software for the automated evaluation of 3D street data has now been developed for Deutsche Telekom and refined to enable these data gaps to be filled in. The new software detects cars in the camera images via semantic segmentation and deletes them from the data. Generative AI then fills in the erased areas and the car-free image is projected into the point cloud. The resulting car-free 3D point cloud forms the basis for digital planning maps. The software also makes it possible, for the first time, to segment the measurement images according to usable floor area types such as sidewalks, highways and parking lots.

As well as closing the data gaps, this release also significantly improves software performance: By means of parallelization and flexible use of the hardware resources available on the computer, the measurement data is now processed in half the time compared to before. This makes it far more cost-effective to process vast amounts of data in the cloud.

"We can automatically remove interfering objects such as parked cars from 3D point clouds."

*Benedikt Rombach, Group Manager*

The Fraunhofer's BAU-DNS flagship project

## LiDAR sensor accelerates building renovations

The construction sector plays a key role in the fight against climate change: The preservation of existing buildings alone makes it possible to save energy and resources. Efficient building insulation and the installation of thermal insulation glazing improve the energy efficiency of buildings.

In Fraunhofer's BAU-DNS flagship project, which has been running since January 2023, seven Fraunhofer institutes are working on making thermal retrofits more efficient and more sustainable. Fraunhofer IPM is developing an optical sensor that makes it possible to capture buildings completely, quickly and flexibly. This involves the use of LiDAR technology combined with cameras. The resulting point cloud can be interpreted in real time using AI – the sensor provides users with direct feedback on the capture process and the quality of the building scan.

In this project, Fraunhofer IPM is drawing on its experience in the "3D AI" field and in setting up multimodal measurement systems, including T-Cars that survey and digitalize entire stretches of road while driving by, to advance the fiber-optic expansion. Initial measurements taken at two demonstrator buildings have yielded extremely promising results. During the next phase of the project, the collected data will be used to create a digital twin that can help to plan renovations with greater accuracy and efficiency. It is possible to prefabricate individual components and modules in one modular system – a resource-friendly and sustainable process that benefits the environment.

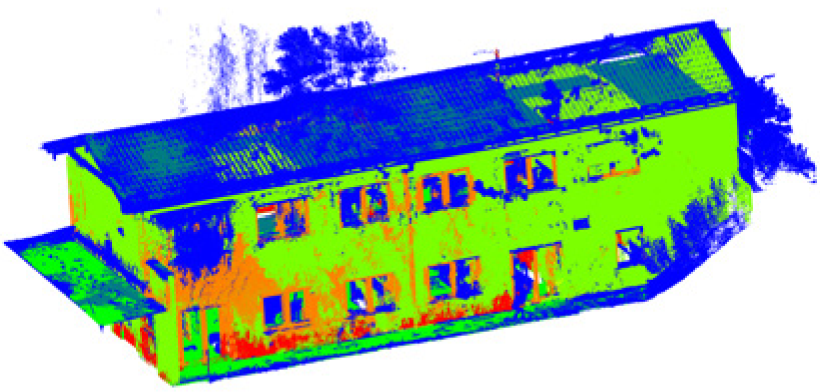
**BAU-DNS (A comprehensive process for building refurbishment that is sustainable, modular and circular) project, funded by the Fraunhofer-Gesellschaft (Flagship project)**

Fraunhofer / University cooperation program

## Successful cooperation with Furtwangen University will continue

Analysis, semantic segmentation and data visualization – these themes are becoming ever more important in the world of 3D measurement technology and they play a key role in areas such as building renovation. Fraunhofer IPM has been successfully collaborating with Furtwangen University (HFU) in this area of research for several years now. It all began with individual research projects. In 2019, the Smart Data Processing and Visualization group was then set up. Under the leadership of Professor Christoph Müller, who holds the professorship for computer graphics in the Digital Media Faculty at the HFU, this group celebrated a whole host of successes, including the development of software capable of performant visualization and annotating of point clouds.

The Fraunhofer Cooperation Program with Universities of Applied Sciences (UAS) provided financial support for the collaboration between Fraunhofer IPM and the HFU. The five-year funding period came to an end in 2023, but the successful collaboration continues: In early 2024, Benedikt Rombach took over the leadership of the group, which has since grown to include ten employees and now goes by the name of 3D Geodata Analytics. Further joint projects between Fraunhofer IPM and the HFU are in the pipeline. Supporting students is also on the agenda: Many master's theses have been produced and several more are in the planning phase. This collaboration meant that automated measurement data evaluation expertise could be pooled and consolidated, to the benefit of both partners.



*Optical sensors from Fraunhofer IPM can capture buildings quickly and flexibly. The generated point clouds can be interpreted in real time using AI.*

# **Object and Shape Detection |** Trade Fairs & Events

## BAU

April 04–22, 2023
Stand of the Fraunhofer Building Innovation Alliance

We presented a 3D modeling software framework for construction planning based on AI.

## INTERGEO

October 10–12, 2023

The interactive live demonstrator 3D-AI for AI-based, automated evaluation of mobile mapping data was on display. Prof. Dr. Alexander Reiterer gave a presentation on the “Evaluation of mobile mapping data with AI for an accelerated expansion of the German fiber optic network”.

## Fairs & events in 2024

**Oceanology International**
March 12–14, 2024

**INTERGEO**
September 24–26, 2024

**InnoTrans**
September 24–27, 2024

**Hydro**
November 05–07, 2024

**MoLaS – Mobile Laser Scanning Technology Workshop**
November 27–28, 2024

# **Focus** Optical building inspection

## An alternative to the impact hammer test: A laser makes hidden damage to buildings visible.

*Cavities or spalling can be concealed beneath the surface of a concrete wall. Defects like these can now be detected using a pulsed laser.*

Prevention always makes sense, and not just when it comes to our health. Checking the condition of tunnels, bridges, dams, canals and other infrastructure buildings on a regular basis is also recommended. Minor building defects are often the first signs of impending major damage. Discovering these in good time should therefore form part of predictive maintenance. When it comes to status monitoring, many infrastructure operators still rely on visual inspections. Specialist inspection companies also use mobile laser scanners to measure building geometry and detect surface defects. But what about damage below the surface? A team at Fraunhofer IPM has shown that lasers can also detect damaged areas that lie hidden beneath the surface. In the future, the method developed as part of the LaserBeat project is set to replace the mechanical impact hammer test, which is the standard method currently used for testing building integrity.

### Objective measurement results instead of subjective perception

During the impact hammer test, a special testing hammer is used to tap the entire surface – no mean feat, considering the size of most of the objects being tested. The only sensor used in the impact hammer test is the human ear. It perceives the resonance vibrations triggered by the hammer and draws conclusions about material changes under the surface from the changes in vibration strength. This testing method does not produce objectively quantifiable measurement results. It is virtually impossible to make comparisons over long periods of time that would indicate emerging defects. Innovative methods that make it possible to deliver objective digital measurement data and enable up-to-date maintenance in accordance with the Building Information Modeling (BIM) principle are therefore very much in demand.

### Strong pulsed laser triggers characteristic surface vibration

Researchers at Fraunhofer IPM imitate the mechanical impact hammer using a pulsed Nd:YAG laser with just under 1 J pulse energy and 5 ns pulse duration. The laser is pointed at the building surface from a distance of between one and ten meters and with a repetition rate of 10 Hz. It creates plasma in the air right above the object's surface without damaging it. If material delaminations, cavities or defects are present underneath the surface, the plasma-induced shockwave triggers characteristic resonance vibrations on the surface – in a similar way to a hammer.

Typical defects that can be detected using the hammer method show resonance frequencies of a few 100 Hz up to around 10 kHz. While testing staff interpret the resonance vibrations that result from the impact hammer test, the vibrations during remote laser-based detection are picked up using a second laser: A laser doppler vibrometer (LDV) measures the mechanical vibration of the concrete surface directly via the doppler shift of the backscattered light, which is then evaluated using interferometry. The amplitudes and frequencies of the vibrations provide information about the size and depth of the cavities and defects. The team has built an LDV designed specifically for delamination testing in tunnel structures and optimized to detect defects in concrete walls as well as handle the conditions in the tunnel.

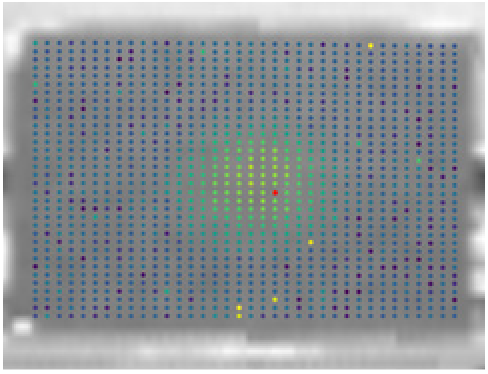
### Efficient and more sensitive than manual testing methods

When taking test measurements on a concrete block that had artificial defects of varying sizes made of extruded polystyrene foam embedded a few centimeters under the surface, the laser-based system proves to be superior to the traditional impact hammer test: The laser-induced structure-borne sound reliably detected defects of up to 12 × 12 $cm^2$ in size, which were not identified using the manual, mechanical method. The measurements were taken from a distance of two meters. The system was then tested under real conditions by taking measurements in several selected tunnels. Once again, the method was proven to be robust and reliable.

A rotating deflection mirror deflects the laser beam along two axes, making it possible to capture a surface area. The essentially stationary structure can be integrated into a robotic platform to inspect large areas, enabling it to take measurements at fixed intervals in stop-and-go mode. The system takes just over 15 minutes to test an area of around 100 $m^2$ with a measuring grid of 10 cm, or even less time, with a lower resolution. Further parallelization and optimization of system components is set to speed up the recording process even more in future.

"This method enables us to test structural integrity faster and more accurately than ever before."

*Valentin Vierhub-Lorenz, Project Manager*



*AI-based data evaluation: A software developed by Fraunhofer IGP identifies prominent measuring points, isolates damaged areas and instantly visualizes the results. Bright measuring points indicate delamination in the center of the test specimen. Each measurement signal can also be displayed in detail as a graph.*

# **Overview** Gas and Process Technology

## Developing customized measurement systems and energy converters: That is our contribution to greater sustainability.

Within our Gas and Process Technology business unit, we develop and produce measurement and control systems to fit our clients' briefs. Applications range from exhaust gas analysis and food transit monitoring to sensors and systems used to measure minuscule temperature differences. Short measurement times, extreme accuracy and high levels of reliability are the hallmarks of our systems – no matter how extreme the conditions.

We also develop, design and assemble systems capable of pumping, converting, transferring and controlling heat. We are researching caloric heat pumps and cooling systems, thermoelectric modules and temperature control systems, as well as heat pipes and heat pipe-based thermal switches.

**Miniaturized sensors and systems**

**Spectroscopy methods**

**Quantum sensor methods**

**Cooling with caloric systems**

**Heat transfer via heat pipe**

## Our groups and focus areas

### Integrated Sensor Systems

- Gas-sensitive materials
- Micro-optic infrared components
- Miniaturized gas sensor systems

### Spectroscopy and Process Analytics

- Spectroscopy analytics
- Optical systems
- Evaluation methods

### Nonlinear Optics and Quantum Sensing

- Nonlinear optics
- New spectroscopic measurement techniques
- Quantum sensor technology

### Thermal Measurement Techniques and Systems

- Customized microstructures
- Thermal measurement systems
- Simulation of physical processes
- Innovative Peltier cooling and thermal management
- Structural, thermal and electrical analytics of components and materials

### Caloric Systems

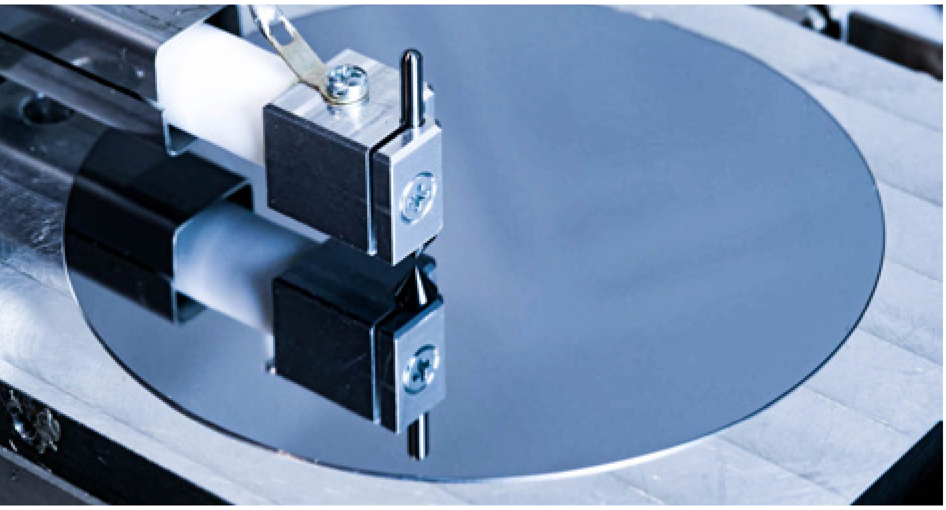
- Heating and cooling without harmful refrigerants
- Development of magnetocaloric, elastocaloric and electrocaloric systems
- Development and characterization of heat pipes for thermal management

**We’re developing measurement systems that detect gas leaks remotely. That means we’re ensuring safe gas infrastructure.”**

Professor Jürgen Wöllenstein, Head of Department

# **Highlights** Gas and Process Technology

## Projects • Innovations • Events



*Writing the easy way: A new method makes it possible to write polarization patterns into lithium niobate crystals – flexibly and with no need for time-consuming mask fabrication.*

Structuring without masks

### New manufacturing procedure for periodically poled lithium niobate

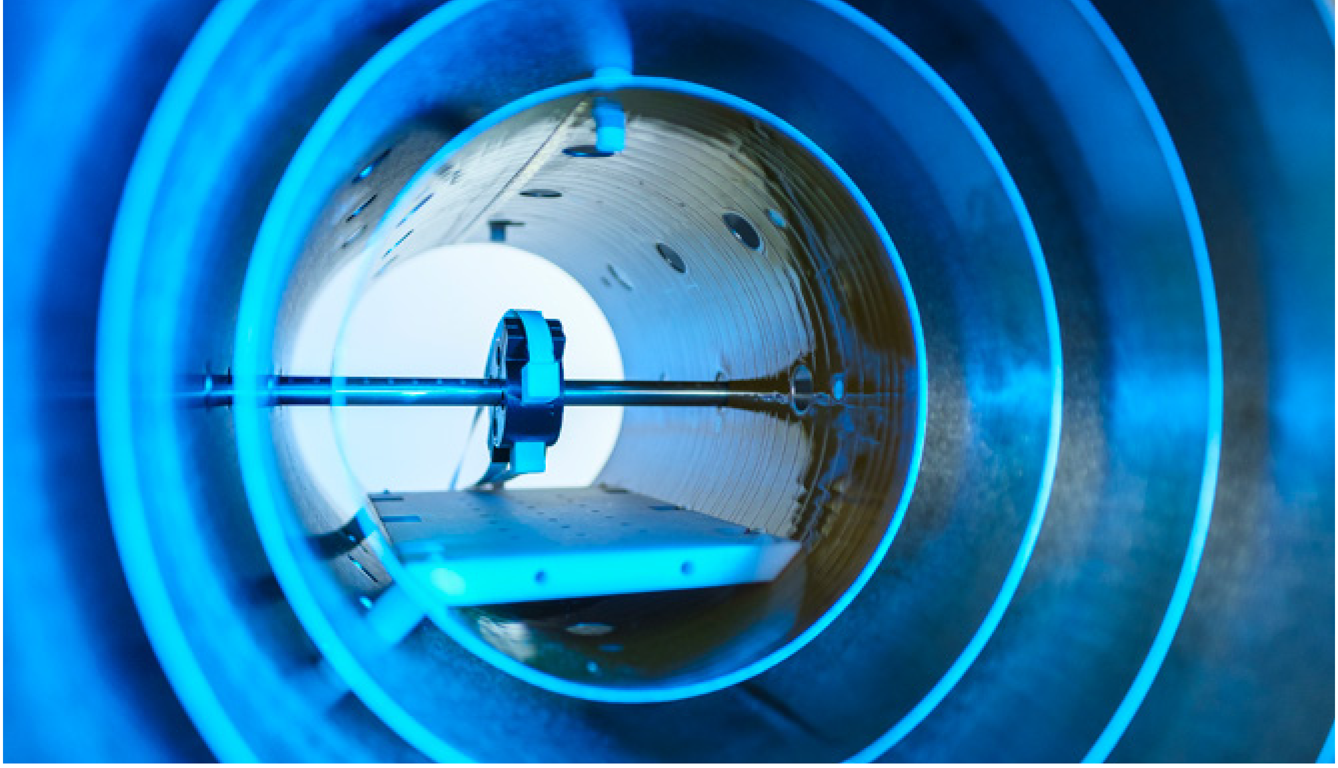
Lasers with specific wavelengths are essential in measurement technology and analytics, as well as for assembling quantum computers and atomic clocks. Nonlinear optical crystals offer a way to produce the desired wavelength. Periodically poled lithium niobate (PPLN) is a nonlinear optical crystal with very particular photonic properties that make it suitable for laser light frequency conversion. Researchers at Fraunhofer IPM have worked with the University of Freiburg to develop a new method to structure PPLN in a flexible way and without the need for masks.

The previous method used to manufacture PPLN crystals is time-consuming, expensive and inflexible, making it only really suitable for mass-producing PPLN crystals. The newly developed method does away with the need for masks as well as the exposure step that previously had to take place in a cleanroom; instead, researchers write the desired polarization patterns directly into the material using a tungsten tip. This has many advantages, including short throughput times, more flexibility with polarization patterns, and the opportunity to produce small batches and one-offs.

The New-VIEUW project

### Next-generation wavelength measurement system

The ability to accurately measure the laser wavelength is crucial in many laser applications. But sufficiently accurate measuring devices are only available for the visible and near-infrared wavelength range (NIR). As a result of the New-VIEUW project, Fraunhofer IPM and its partners presented the prototype of a high-precision wavelength measuring device for the mid-infrared (MIR) range. The concept centers around a wavelength range extender that converts the infrared light to be measured into shorter wavelengths in a nonlinear crystal via sum frequency generation (SFG). Fraunhofer IPM devised the conversion concept and supported the development of the periodically poled lithium niobate (PPLN) waveguide via project partner Covesion Ltd. by providing simulations and materials investigations. We have designed and



developed an appropriate upconversion module on that basis. The module makes it possible to determine the desired MIR wavelength with the utmost precision using a silicon detector array, which measures the up-converted NIR wavelength in a specially adapted wavelength measurement system from project partner High Finesse GmbH.

The result significantly surpassed the project's goals and shows such great promise that there is nothing standing in the way of the prototype's commercialization. Alongside MIR laser manufacturers and users of precision spectroscopy, upconversion waveguide technology has also captured attention in the MIR imaging, sensor technology and LiDAR markets. The New-VIEUW module can serve as the basis for further customized developments.

**New-VIEUW (Next generation WaVelength meters for the mid-Infrared Enabled by Upconversion in Waveguides) project, funded by the EU (Eurostars program)**

The QMag project

## Non-invasive flow measurement using magnetic quantum sensors

Determining the flow rate of liquids through a pipe is essential in many industrial processes. A groundbreaking new method enables, for the very first time, flow to be accurately measured without calibration and using a non-invasive approach. This technology, developed as part of the QMag project completed in 2023, uses the effect of the nuclear spin of hydrogen atoms, whereby the atomic nuclei align themselves according to magnetic fields: Flow is measured by polarizing the unmagnetized liquid using a magnet. As it flows through the pipe, the magnetization is changed locally through a high-frequency pulse. The marked liquid continues to flow and is then detected using a quantum sensor. The time difference between the marker and detection can be used to calculate the flow rate. With this method, it is possible to measure flow rates in the range of 0.1 m/s to 3.1 m/s. Our researchers use a highly sensitive optically pumped magnetometer (OPM) as the detector, creating a weak magnetic field that is sufficient to mark the liquid. This makes the method suitable for stainless steel pipes, too.

In accordance with the quantum magnetometry principle, the flow of all liquids containing hydrogen can be measured – including oils, foods and cosmetics. The team will continue to refine the system into a clamp-on detector and extend its functionality to measure the flow rate of multi-phase flows.

**The QMag (Quantum Magnetometry) project, funded by the Fraunhofer-Gesellschaft (Flagship project)**

**Video: The principle of flow metering based on quantum magnetometry**

*No larger than a sugar cube and well shielded: A highly sensitive quantum sensor measures flow in a steel pipe.*

> "Our sensor opens up new perspectives when it comes to flow measurement technology."

*Dr. Peter Koss*
*Project Manager*


*In future, a quantum magnetometric camera is set to detect the first signs of cracks in materials during component production.*

The QuMa2 project

## Magnetic field camera for highly sensitive crack detection

Hidden damage in materials on a minute scale bear the risk of growing into cracks over time and endanger the functionality and safety of technical plants and systems. Discovering defects of this kind during manufacture is key for quality assurance. In ferromagnetic materials, inhomogeneities in the magnetic field strength indicate microcracks. These magnetic signals are within the range of a few picoTesla, making them a million times weaker than the earth's magnetic field. Highly sensitive magnetometers are required to detect them.

During the QuMa2 project, which launched in October 2023, teams from Gas and Process Technology and Production Control work together to develop a highly sensitive magnetic field camera capable of producing images to measure the magnetic field strength of components and suitable for use in production environments. The camera is expected to inspect a complete surface area of a few $cm^2$ to $dm^2$ with a spatial resolution of around 100 micrometers in just a few seconds. For the first time, researchers are using optically pumped magnetometers (OPM) to achieve high levels of sensitivity and spatial resolution alongside high measuring rates. The highly sensitive quantum sensors, used in conjunction with real-time image processing, are set to enable a non-destructive in-process inspection of micro-defects using imaging techniques for the first time. The camera will read around one thousand measuring points simultaneously, enabling a high measuring speed in comparison to point-measuring sensors.

**QuMa2 (High-resolution quantum magnetometric camera for fast inline materials testing) project, funded by the German Federal Ministry of Education and Research (quantum systems research program)**

The MAGGIE project

## New magnetic shielding concept for space instruments

Magnetic fields can interfere with the functionality of highly sensitive space instruments. This means that the ability to permanently control the magnetic cleanliness of components and their magnetic shielding is an absolute must for any mission into outer space. Strict limits apply here. Keeping within this "magnetic budget" is challenging, as – alongside cosmic magnetic fields –, it is usually the technical components in satellites and spaceships, such as permanent magnets, that generate magnetic fields.

Researchers at Fraunhofer IPM, Fraunhofer EMI and Fraunhofer ISC are aiming to improve the magnetic shielding of space travel instruments through an innovative concept: In the MAGGIE project, which began in fall 2023, they are developing a spray coating technology on behalf of the European Space Agency ESA that aims to protect space components from magnetic fields more effectively than before. The team is developing new coating materials that can be applied as a very thin layer to various substrates and customized components. The work conducted at Fraunhofer IPM focuses on extremely sensitive magnetic field measurements taken in a magnetically shielded room (MSR).

**MAGGIE (Innovative Materials and Designs for Magnetic Shielding) project, funded by the European Space Agency ESA**


*The miniaturized non-invasive breath gas sensor can be integrated into ventilators using a t-connector.*

The PASMIE project

## Medical imaging using photoacoustics

Photoacoustic Imaging (PAI) has the potential to markedly improve medical diagnostics on soft tissue using a combination of optical and acoustic methods. The very nature of traditional ultrasound-based methods limits the applicability in this field. Certain tissue components such as blood vessels absorb visible or infrared light to varying degrees, resulting in differing contrasts during photoacoustic imaging. The very first commercially available PAI systems use expensive tunable high-power lasers as a light source, as well as converters originally developed for ultrasound imaging, and they connect the probe to a stationary signal processor via long coaxial cables that are susceptible to noise. Sensor systems designed and optimized for photoacoustic imaging are still lacking.

Using a novel fusion of different technologies and methods, researchers at Fraunhofer IPM working on the PASMIE project are aiming to develop the very first highly sensitive probe for photoacoustic imaging in medical technology. Central to this is the integration of ultrasound converters and light sources within one housing. This will enable higher integration density and minimized costs thanks to the use of laser diodes. Specific reconstruction algorithms and fast repetition rates with low energy consumption are set to optimize the system even further. In addition, the monolithic integration of signal processing into the ultrasound converter results in an improved signal-to-noise ratio – by an entire order of magnitude in comparison to existing systems.

**The PASMIE (Photoacoustic probe for medical imaging) project, funded by the Fraunhofer-Gesellschaft (PREPARE project)**

The BREATH project

## Miniaturized breath gas sensor measures oxygen levels

In the BREATH project, which has been underway since January 2022, researchers from Fraunhofer IPM have developed a sensor that monitors oxygen levels in respiratory air and therefore provides precise data about blood oxygen levels. This sensor is set to replace previous conventional measuring methods in the future. Nowadays, pulse oximeters are generally used to determine blood oxygen levels. However, these only provide inaccurate readings. At present, it is only possible to obtain more precise data using invasive arterial blood gas testing, which is expensive, complex and cannot be performed continuously.

For this new breath gas sensor, researchers at Fraunhofer IPM developed and analyzed fluorophore layers that enable oxygen concentration to be determined quickly down to the level of individual breaths thanks to their interaction with oxygen and the resulting fluorescence quenching. The size of the newly developed sensor has now been reduced to the point that it can be connected to commercially available standard T-connectors. This means it can now be connected directly to a ventilation mask or breathing tube, making it easier to integrate the sensor into existing ventilators. In the future, there are plans to simplify the measurement system to make it more user-friendly and suitable for use in home care as well as for clinical applications.

**BREATH project, funded by the Fraunhofer-Gesellschaft (SME project)**

*A photoacoustic $CO_2$ detector is characterized in a spectrometer setup.*


*A handheld laser-based spectrometer for remote gas detection measures ammonia leaks using a contactless technique from distances of up to 50 m.*

The PaSiC project

## Technology platform for photoacoustic and optical gas sensors

Among their many applications, gas sensors are used for monitoring air quality for occupational safety purposes, in the automotive sector and in environmental analytics. There are two main limiting factors when it comes to the more widespread use of gas sensors: Firstly, commercial gas sensors consume a lot of energy and secondly, they are large and heavy. There is therefore a demand for cost-effective, energy-efficient sensors that provide long-term stability.

In the PaSiC joint project, completed in mid-2023, Fraunhofer IPM and its research and industry partners developed a technology platform to meet two requirements: Firstly, to enable the realization of robust and miniaturized IR components (radiation sources and detectors) and secondly, novel, cost-effective sensors based on photoacoustic and optical principles. The SiCer hybrid substrate (silicon and ceramic sinter composite) researched during the PaSiC project is best suited for producting optical sensing elements directly on the silicon wafer. Furthermore, it enables the use of LTCCs (Low Temperature Cofired Ceramics) as the wiring level and the traditional hybrid integration of other sensors and electronic components. Among other things, the project produced a photoacoustic $CO_2$ detector using MEMS technology. To characterize this detector, Fraunhofer IPM developed a spectrometer that spectrally resolves photoacoustic detectivity. This allowed researchers to determine and quantify the filling pressure, the composition of the filler gas and the radiation absorption not attributable to gases, which markedly improved the detectors. The spectrometer will also be capable of taking spectrally resolved measurements of future detectors, thereby significantly improving understanding of photoacoustic gas measurement systems.

**PaSiC (Silicon-ceramic hybrid substrate as integration platform for photoacoustic and optical applications) project, funded by the German Federal Ministry of Education and Research (HyMat, hybrid materials – new possibilities, new market potential funding initiative)**

The TransHyDE project

## Sensors for safe hydrogen infrastructure

Hydrogen ($H_2$) plays a crucial role when it comes to the energy transition. In the TransHyDE hydrogen flagship project, partners from science and industry are researching solutions to transport and store the gas safely. This is essential, as this odorless gas is highly flammable and even explosive in high concentrations. As part of "TransHyDE_FP2: Safe Infrastructure", Fraunhofer IPM and its partners are developing new sensors to detect leaks in hydrogen pipelines, storage tanks and supply points. Methods are being developed to enable the reliable detection of hydrogen and hydrogen carrier gases in a wide range of environments and gas mixtures. In 2023, researchers focused on ideas including an ultrasound sensor, a laser-based spectrometer and a Raman spectrometer.

Discovering leaks quickly and reliably is crucial for ensuring the safety of systems that transmit hydrogen. The team from Fraunhofer IPM developed an ultrasound sensor that delivered highly promising measurement results during initial field measurements conducted at industrial partner RMA Rheinau GmbH & Co. KG. The measurement technique is based on the resonance displacement principle and makes it possible to immediately determine the presence of $H_2$: If a gas mixture contains hydrogen, the propagation of sound and sound velocity changes. The change in sound velocity can be used to determine the concentration of hydrogen. The next step is for the team to take measurements in the field.

Fraunhofer IPM has developed a laser-based spectrometer for the remote detection of the toxic hydrogen carrier gas ammonia ($NH_3$). This compact handheld device, measuring $9 \times 16 \times 12$ cm$^3$, enables the contactless detection of $NH_3$ leaks from distances of up to 50 m. Initial laboratory tests were successful, and the next step will be to test the detection device by taking field measurements.

Fraunhofer IPM is also using Raman spectroscopy to detect the presence of hydrogen in gas mixtures. This homonuclear gas is "invisible" to infrared radiation, meaning it cannot be directly detected using traditional infrared absorption spectroscopy. An alternative is to detect hydrogen using thermal conductivity sensors, which indirectly measure $H_2$ concentrations on the assumption that the composition of the gas matrix is known. Raman spectrometers, on the other hand, can selectively and directly detect $H_2$ without cross-sensitivities in concentrations ranging from 0 to 100 percent. However, available Raman systems are designed for broadband spectral analysis, making them complex and expensive. As part of TransHyDE, the team at Fraunhofer IPM is developing a novel Raman sensor that selectively detects and quantifies only $H_2$ – but does so using a signal-optimized approach with narrow-band Raman filters and a large-scale detector. The prototype uses cost-effective components, measures just $20 \times 10 \times 10$ cm$^3$ and detects $H_2$ with an accuracy of 0.1 percent.

**TransHyDE project (TransHyDE_FP2: Safe Infrastructure), funded by the German Federal Ministry of Education and Research (hydrogen flagship project), Project Management Agency Projektträger Jülich (PtJ)**

The AIMS³ project

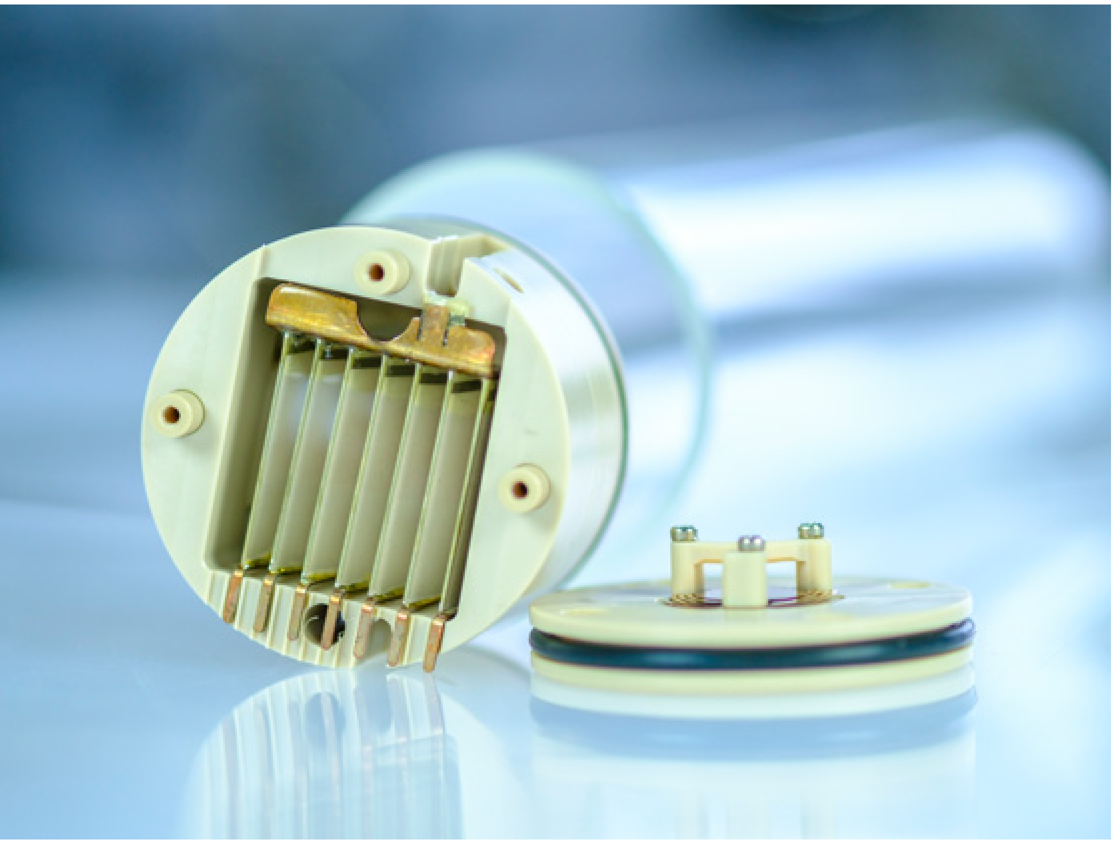
## Sensor technology for monitoring $CO_2$ stores in the ocean

The sea can play a crucial role in the fight against climate change: Layers of basalt lying deep in the seabed can be used to store carbon dioxide ($CO_2$). In the AIMS³ joint project, the project partners are conducting intensive studies and experiments with the aim of showing which technical methods are capable of storing and mineralizing $CO_2$ in basalt rocks in the most cost-effective and sustainable way. But Carbon Capture and Storage (CCS) is associated with environmental risks, particularly if $CO_2$ leaks back out. Leaks therefore need to be traced quickly and thoroughly.

As part of the project, Fraunhofer IPM is developing a novel fast-response sensor to monitor $CO_2$ stores in the seabed. A prototype has been successfully tested under real-life conditions on the Littorina research ship in the Baltic Sea. The membrane-free sensor is based on ATR (Attenuated Total Reflection) spectroscopy. Using this method, the optical sensor detects the amount of $CO_2$ dissolved in the harsh seawater environment within a matter of seconds, which means $CO_2$ leaks can be discovered quickly. In the second phase, which is due to begin in August 2024, the sensor will be optimized and reduced in size to enable it to withstand higher pressure and make it suitable for use in deep waters.

**AIMS³ project (Alternate scenarios, Innovative technologies, and Monitoring approaches for Sub-Seabed Storage of carbon dioxide, part of the CDRmare Research Mission of the German Marine Research Alliance (DAM) "Marine carbon sinks in decarbonization pathways"), funded by the German Federal Ministry of Education and Research (MARE:N – Coastal, Marine and Polar Research for Sustainability research program)**

*Tracing leakages at $CO_2$ stores in the seabed: The sensor based on ATR spectroscopy has already been tested in the Baltic Sea.*



*An electrocaloric cooling system based on ceramic materials achieves an unprecedented specific cooling power of 1.5 W/g.*

"

A high power density is essential for the commercialization of electrocaloric cooling systems."

*Dr. Kilian Bartholomé, Group Manager*

The ElKaWe project

## Electrocaloric cooling system achieves power density record

As part of the ElKaWe project, a team from Fraunhofer IPM is conducting thorough research into electrocaloric (EC) cooling systems. In 2023, the researchers took a decisive step forward. In an article that was published in the prestigious "Communications Engineering" journal, they presented the prototype of a ceramic EC cooling system with an unprecedented specific cooling power of 1.5 W/g. The system, which uses lead scandium tantalate (PST) as the EC material, surpasses previous ceramic EC material-based systems by an entire order of magnitude.

The key innovation is optimized heat transfer: The prototype works with an active electrocaloric heat pipe (AEH), which uses evaporation and condensation of a fluid – ethanol in this case – as a heat transfer mechanism. The team had already used this latent heat transfer concept for magnetocaloric and elastocaloric heat pumps and is now putting it into effect in an electrocaloric heat pump for the first time. It enables a high cycle frequency of 5 Hz and a higher specific cooling power compared to systems with alternative forms of heat release, such as convective or solid-state heat transfer.

**Scientific publication: »Electrocaloric cooling system utilizing latent heat transfer for high power density«**

The MagMed 2/ElKaWe projects

## Efficiency potential of caloric materials quantified

Caloric heat pumps are based on elastocaloric, magnetocaloric, electrocaloric or barocaloric solid materials. By applying a magnetic or electrical field, or when put under mechanical stress, the temperature of the material changes. Depending on the type of material, this can lead to hysteresis during a phase transition, which in turn results in dissipative heating. This has a negative impact on the efficiency of the heat pump. But how can different materials be assessed quickly and reliably with regard to the efficiency of caloric systems? One decisive factor here is the coefficient of performance, also known as the figure of merit (FOM). The FOM is defined as the relationship between the adiabatic temperature change and the thermal hysteresis.

A research team, led by Fraunhofer IPM, has used literature data to compile an overview of the FOM of 36 different caloric materials and compared their potential efficiency with the efficiency of current compressor systems. The results showed that, in principle, certain caloric materials already enable systems to reach efficiency levels that are not even theoretically possible with compressor systems. Even if this efficiency potential has still not been completely achieved in experimental caloric systems, the development of materials gives cause for hope: Over the past three years, the FOM for electrocaloric and barocaloric materials has tripled.

**MagMed 2 project, funded by the German Federal Ministry for Economic Affairs and Climate Action; ElKaWe project, funded by the Fraunhofer-Gesellschaft (Flagship project)**

The MagMed 2/ElKaWe projects

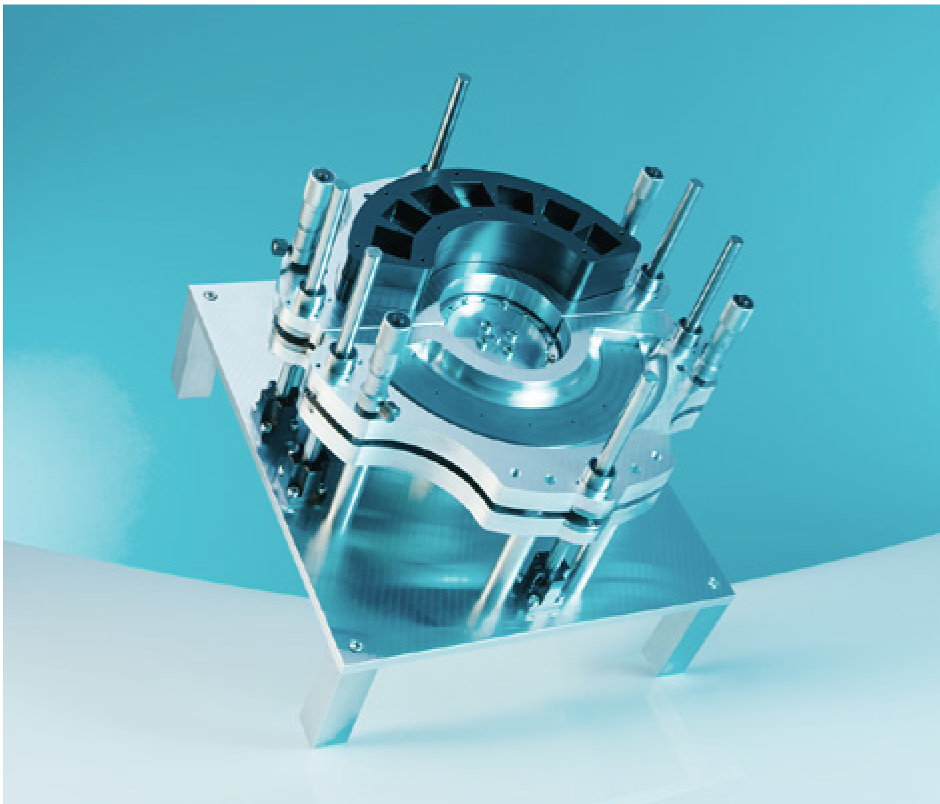
## New measuring method to determine the efficiency of caloric materials

Heat pumps play a crucial role in the fight against climate change. Caloric heat pumps promise significantly higher levels of efficiency compared to conventional pumps and do not require the use of harmful coolants. In several projects, we are working on the development of efficient heat pumps and cooling systems based on caloric systems.

The efficiency of caloric heat pumps largely depends on the caloric material. Thorough research into suitable materials is currently being conducted. In order to better compare different caloric materials in terms of their suitability for heat pumps, Fraunhofer IPM has introduced a new metric (figure of merit, FOM) and developed appropriate measuring methods. This material measurement focuses on quantifying dissipative heat with extreme accuracy – that is, determining heat loss. Even low amounts of dissipated heat significantly reduce the system's overall efficiency. The cyclic self-heating method (CSH) is based on a simple determination of the temperature profile of a probe by applying a particular field profile. The simple measuring setup makes it possible to evaluate the efficiency potential of caloric materials in a cost-effective and accurate way.

This enabled the team to determine, for example, the dissipative heat and therefore the FOM of a lanthanum-iron-silicon-based probe. The result: This magnetocaloric material has a very high level of efficiency, with a theoretical maximum efficiency level of over 90 percent. This makes the material a highly promising candidate for future caloric cooling systems and heat pumps.

*Turning the inner ring of a Halbach magnet system generates a defined field profile. This makes it possible to determine the efficiency of magnetocaloric materials.*



*Small powerhouse: High load SMA actuators generate high forces in small spaces. Peltier modules (left) provide effective heat dissipation and therefore enable high cycle frequencies. (Photo montage)*

The Spin-TEC project

## Peltier modules to increase the thermal stability of motor spindles

The thermal behavior of motor spindles in machine tools is crucial when it comes to their working precision. Electrical and mechanical power losses in the motor and the bearing result in the induction of heat flow in parts of the spindle, such as the pinion and the housing, which then distorts them – with a negative impact on precision. Long warm-up periods are therefore required to ensure the machine tool reaches a thermally stable state. Only then can manufacturing tolerances in the sub-micrometer range be reached, as required in cases such as precision components in medical technology, the aerospace industry and toolmaking. During operation, however, fluctuations in the induced heat flow and therefore the thermally induced shift are unavoidable, owing to factors such as tool and workpiece changeover as well as adjustments to the spindle speed.

In the Spin-TEC project, which began in November 2023, a team from Fraunhofer IPM is working with researchers from the Institute of Machine Tools and Factory Management at TU Berlin and two industrial partners to develop a novel thermoelectric temperature-controlled motor spindle. The concept centers around tubular Peltier modules, which are integrated between heat sources and heat sinks, thereby enabling regulated temperature control of the bearing and the motor. The greater thermal stability of the motor spindles is set to reduce the warm-up period compared to the conventional approach. At the same time, the thermoelectric temperature-controlled motor spindles are expected to increase the working precision of machine tools and enhance machining process productivity.

**Spin-TEC (Thermoelectric temperature control for motor spindle in high-precision machine tools) project, funded by the Fraunhofer-Gesellschaft and the German Research Foundation (trilateral transfer project)**

The HochPerForm project

## Dynamic high load actuators thanks to effective cooling

Actuators are used in many toolmaking and mechanical engineering applications. In an ideal scenario, these components can generate and rapidly activate very high forces in small spaces. This is where hydraulic, pneumatic and piezo actuators reach their limits. As part of the HochPerForm project, a team consisting of researchers from Fraunhofer IWU, Fraunhofer IFAM and Fraunhofer IPM has developed compact high load actuators based on thermal shape-memory alloys (SMAs). With a diameter of just 15 mm and a height of 16 mm, one of the project's demonstrators lifts masses of up to 500 kg by up to 200 µm. This enables components to be accurately positioned in production machines, among other applications.

Actuators based on shape-memory alloys generate displacement by changing the structure of the material, which expands through heating. It is crucial for the dynamics of the actuator that the material cools down quickly enough and returns to its original shape. In the case of high load actuators, this can take several minutes when convection occurs naturally, due to the unfavorable volume-to-surface ratio. The team at Fraunhofer IPM has developed two innovative cooling concepts for high load SMA actuators, which ensure effective heat release while also keeping the system size compact. These concepts are switchable heat pipes and circular Peltier modules, which are capable of dissipating heat at such a rate that the actuator can be switched with a cycle frequency of more than 0.3 Hz. Thanks to the new temperature control, SMA actuators can be easily regulated, enabling a simple system configuration.

**HochPerForm project, funded by the Fraunhofer-Gesellschaft (PREPARE project)**

# **Gas and Process Technology |** Trade Fairs & Events

## 10th Gas Sensor Workshop

March 16, 2023
Fraunhofer IPM

The gas sensor community met in Freiburg to discuss technological trends in gas sensor technology. The program featured eight presentations from research and industry.

## Sensor+Test

Mai 09–11, 2023
Joint booth of the Fraunhofer-Gesellschaft

The entire range of measurement and control systems for gas and process technology was on display, including gas sensors, laser spectroscopic methods for gas analytics and thermal sensors.

## LASER

June 27–30, 2023
Joint booth of the Fraunhofer-Gesellschaft

At the World of Quantum, we presented our latest research results and applications in quantum sensor technology. At the World of Photonics, we displayed our developments in the field of lasers, e.g., optical parametric oscillators for continuous wave operation.

## Quantum Effects

October 10–11, 2023
Joint booth Baden-Württemberg

We gave a presentation to demonstrate the features and possibilities of the magnetically shielded room (MSR) at Fraunhofer IPM. Together with other Fraunhofer Institutes in Freiburg, we also presented the Freiburg Quantum Sensor Hub.

## OPM-MEG Workshop

December 12–13, 2023

In cooperation with the Intelligent Machine-Brain Interfacing Technology (IMBIT) research center in Freiburg, Fraunhofer IPM organized the first OPM-MEG workshop. The workshop focused on the use of optically pumped magnetometers (OPM) for magnetoencephalography (MEG).

## Fairs & events in 2024

**ACHEMA**
June 10–14, 2024

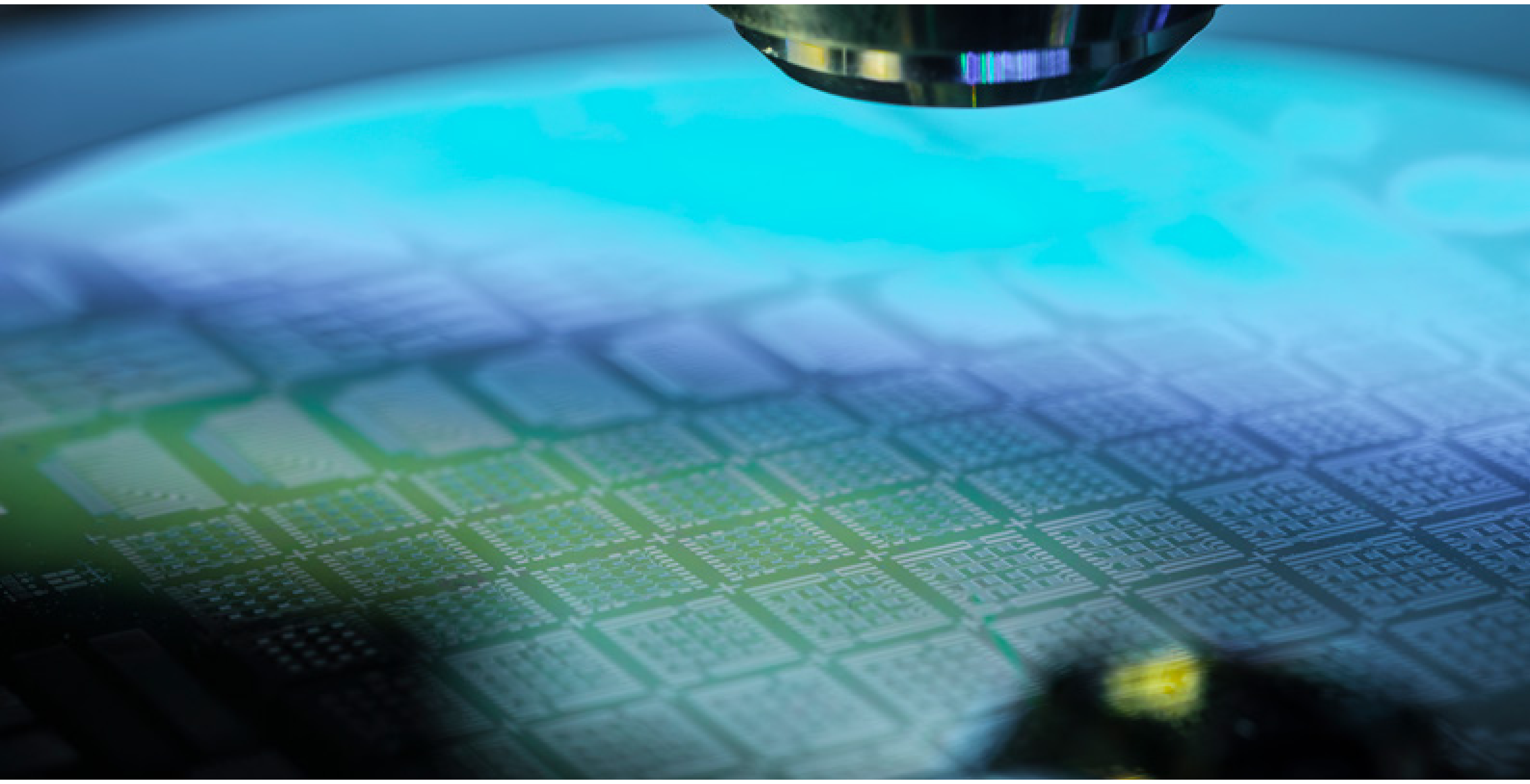
**SENSOR+TEST**
June 11–13, 2024

**CHILLVENTA**
October 08–10, 2024

**Quantum Effects**
October 08–09, 2024

# **Focus** Sensors for temperature measurement

## Miniaturized thermopile arrays: Non-contact temperature measurement with a high degree of sensitivity



*Highly sensitive thermopile arrays – in this case on a silicon wafer – measure temperatures ranging from 0 to 80 °C, accurately to within a tenth of a degree Celsius. This makes them an interesting concept for many new applications.*

Miniaturized thermopile array sensors play an increasingly important role when it comes to measuring temperature. Thanks to their highly sensitive and contactless measuring method, they have the potential to revolutionize numerous areas of application – from temperature control to safety technology and process control. They can detect movements and the presence of people, monitor ceramic hobs and take someone's temperature without contact, among other applications. Many of these tasks can also be carried out by traditional infrared detectors, such as photodetectors, bolometers and pyroelectric sensors, but these detectors are more expensive, more complex or simply not sensitive enough. If the specific aim is object capture by measuring temperature, pyroelectric sensors have the added disadvantage that they cannot capture static objects.

### Thermopile array sensors – design and development

Thermopile array sensors essentially consist of three components: a lens, an IR band-pass filter and an infrared detector array made from thermopiles. Thermopile arrays detect the IR radiation of an object according to its surface temperature. They are cost-effective, do not require an external power supply and can detect both static and moving objects over larger distances and areas thanks to their matrix arrangement. They comprise n- and p-type semiconductor elements that are connected thermally in parallel and electrically in series. These semiconductor elements, also known as thermopiles or thermoelements, use the Seebeck effect and convert thermal energy directly into electrical energy: Depending on the temperature, an electrical voltage is created at the junction point of the two thermoelectric materials and this can be easily measured to a high degree of sensitivity.

Thermopile array sensors can already be customized and optimized in terms of spectral sensitivity for use in many applications. But the standard CMOS-compatible silicon thermopile arrays also have a major limitation: They can only measure temperature with poor accuracy.

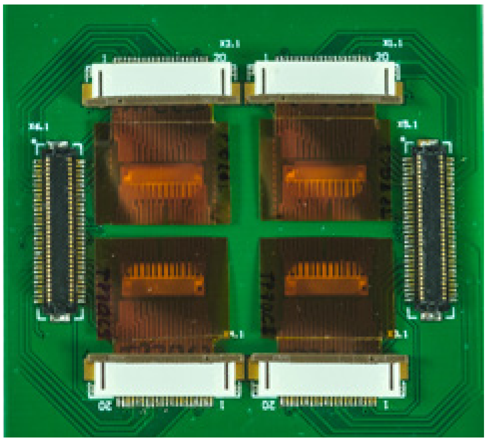
## Greater measuring accuracy opens up new possibilities

Unfortunately, thermopile array sensors currently on the market are unsuitable for many otherwise promising applications due to this limited measurement accuracy. As part of the in-house Fraunhofer TAPIR project, a team from Fraunhofer IPM has therefore developed highly sensitive miniaturized thermopile arrays. To achieve this, the researchers used the material bismuth telluride ($Bi_2Te_3$), which has a particularly high thermoelectric figure of merit at room temperature.

A single thermoelement comprises two semiconductive materials: n-bismuth telluride and p-bismuth antimony telluride. The original idea of applying the thermopiles to a polymer substrate was rejected during the project. Instead, over the course of the project, the team opted to use the well-known silicon substrate optimized using a thin polymer layer. The entire thermopile array of the novel thermal imaging camera from Fraunhofer IPM ended up consisting of 8 × 8 of these thermoelements, providing an image resolution of 64 pixels. This may not sound much in comparison to optical sensors, but this resolution is ideal for taking high-precision temperature measurements in many applications. The team was able to measure temperatures ranging from 0 to 80 °C, accurately to within a tenth of a degree Celsius. It is not only the industry that will benefit from these high-precision thermopile array sensors; among other applications, the sensors can also make life safer for elderly or infirm people living in their own homes, because they can detect critical situations and automatically raise the alarm. And when it comes to object monitoring, the sensor’s 64-pixel image can, for example, safely differentiate between people and animals without violating privacy rights. Many highly promising conversations are already taking place, mainly with small and medium-sized businesses, with the aim of opening up new areas of application for highly sensitive thermopile array sensors.

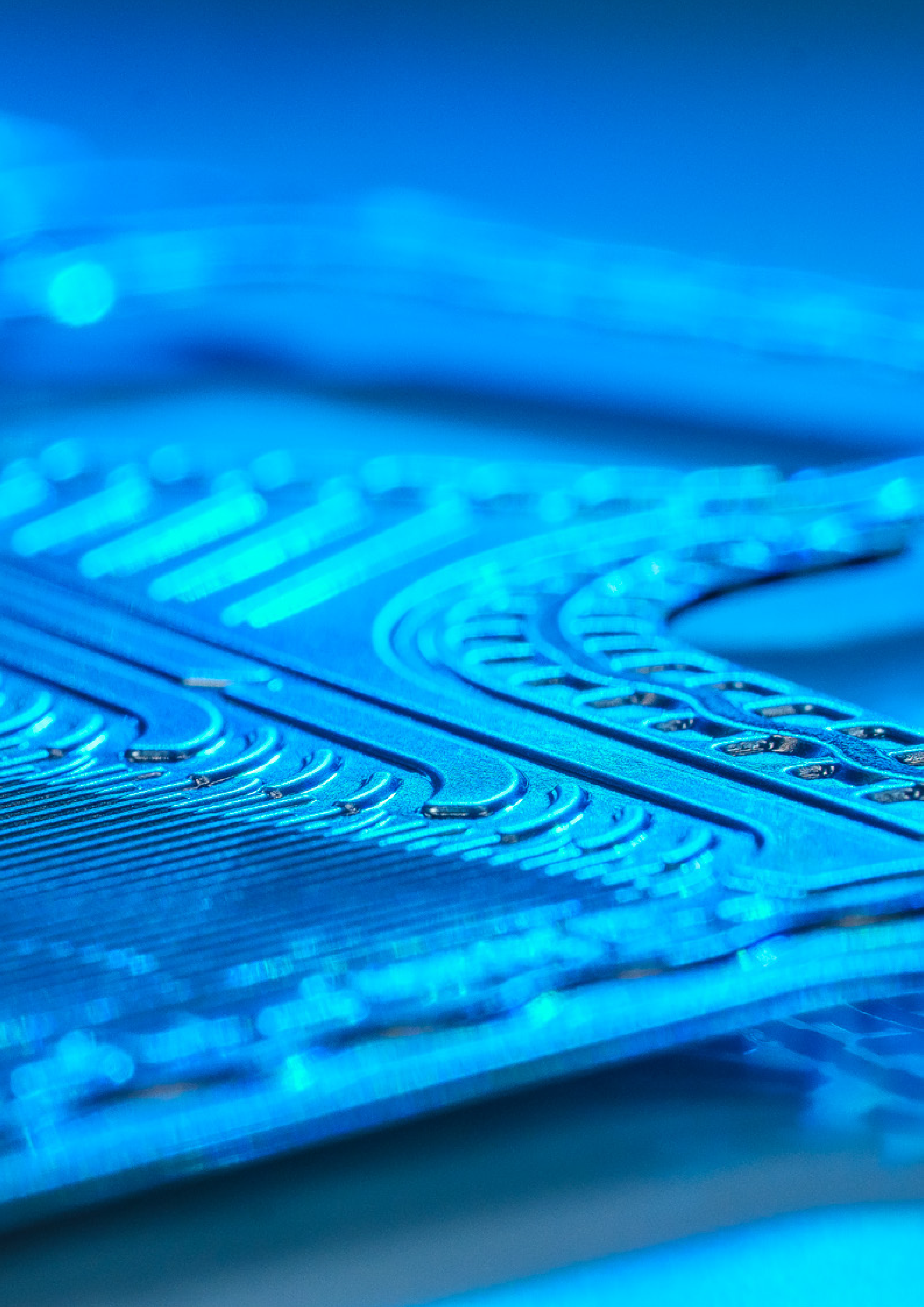
"Many applications involving temperature measurement will benefit from our highly sensitive thermopile arrays."

*Professor Jürgen Wöllenstein, Head of Department*



*First prototype with thermopile arrays, which were initially processed on polymer substrate*

# **Index** Fraunhofer IPM



# **Publications** 2023

Buchta, D.; Adolph, S.; Brandenburg, A.
**A cheap, fast, and versatile illumination system for technical cleanliness**
Georges, M. P.; Popescu, G.; Nicolas Verrier, N. [Hrsg.]: Unconventional Optical Imaging III. Proceedings of SPIE 12136, 1213618 (2022)

Abel, C.; Ayres, N. J.; Ban, G. et al.
**A large "Active Magnetic Shield" for a high-precision experiment**
European Physical Journal C 83, 1061 (2023)

Amiune, N.; Fan, Z.; Pankratov, V. V.; Puzyrev, D. N.; Skryabin, D. V.; Zawilski, K.; Schunemann, P. G.; Breunig, I.
**Mid-infrared frequency combs and staggered spectral patterns in $\chi^{(2)}$ microresonators**
Optics Express 31, 907-915 (2023)

Amiune, N.; Zawilski, K.; Schunemann, P.; Kordts, A.; Holzwarth, R.; Buse, K.; Breunig, I.
**Pump Tuning of a Microresonator Mid-Infrared $\chi^{(2)}$ OPO and Microcomb Generation at 3.1 µm with $CdSiP_2$**
Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC), doi:10.1109/CLEO/EUROPE-EQEC57999.2023.10231917 (2023)

Aslan, M. J.; Seyler, T.; Fratz, M.; Bertz, A.; Carl, D.; Beck, M.; Riedmüller, K. R.; Liewald, M.
**Simulating Holograms from 3D CAD Models via Inverse Hologram Reconstruction for Multiwavelength Holography**
Digital Holography and Three-Dimensional Imaging. Proceedings Optica Imaging Congress, HM1D.1 (2023)

Bach, D.; Winkler, M.; Schäfer-Welsen, O.
**Aus Wärme Strom machen: Biomassefeuerungen als Blockheizkraftwerke**
BWK Energie 75(11-12), 48-51 (2023)

Basler, C.; Kappeler, M.; Carl, D.
**Depth-Resolved Elemental Analysis on Moving Electrode Foils with Laser-Induced Breakdown Spectroscopy**
Sensors 23, 1082 (2023)

Beck, M.; Riedmüller, K. R.; Liewald, M.; Bertz, A.; Aslan, M. J.; Carl, D.
**Investigation on the Influence of Geometric Parameters on the Dimensional Accuracy of High-Precision Embossed Metallic Bipolar Plates**
Lecture Notes in Production Engineering F1163, 427-438 (2023)

Behrendt, V.; Blättermann, A.; Brandenburg, A.
**A fiber-optical fluorescence sensor for in-line determination of cleanliness during cip processes**
Food & Bioproducts Processing 137, 56-63 (2023)

Behrendt, V.; Buchta, D.; Adolph, S.; Lutz, C.; Scherer, J.; Blättermann, A.
**In-line fluorescence detector for production control in robot-driven environments**
Optical Measurement Systems for Industrial Inspection. Proceedings of SPIE 12618, 126181O (2023)

Behrendt, V.; Buchta, D.; Blättermann, A.
**Vollständige Prüfung metallischer Bauteile mittels Fluoreszenz: Beschichtungs- und Reinheitsprüfung in der Produktionslinie**
Inspect 24(4), 54-55 (2023)

Bergau, M.; Strahl, T.; Scherer, B.; Wöllenstein, J.
**Real-time active-gas imaging of small gas leaks**
Journal of Sensors and Sensor Systems 12, 61-68 (2023)

Bernhardsgrütter, R. E.; Hepp, C. J.; Wöllenstein, J.; Schmitt, K.
**Fluid-compensated thermal flow sensor: A combination of the 3ω-method and constant temperature anemometry**
Sensors & Actuators A 350, 114116 (2023)

Blug, A.; Conrad, F.; Bertz, A.; Kontermann, C.; Carl, D.; Oechsner, M.
**Application of high-performance DIC for a comprehensive evaluation of biaxial fatigue crack growth experiments**
Strain 59, e12455 (2023)

Blug, A.; Thiemann, K.; Philipp, S.; Straub, T.; Bertz, A.
**Quantum magnetometry with OPM: Novel applications in non-destructive testing?**
26th IMEKO TC4 International Symposium and 24th International Workshop on ADC/DAC Modelling and Testing, 122-125 (2023)

Busch, S.; Koss, P.; Horch, C.; Schäfer, K.; Schimmerohn, M.; Schäfer, F.; Kühnemann, F.
**Magnetic cleanliness verification of miniature satellites for high precision pointing**
Acta Astronautica 210, 243-252 (2023)

Busch, S.; Koss, P.; Rother, M.; Korte, M.
**Quantum magnetometry as an enabling technology in the New Space domain**
SMSI Sensor and Measurement Science International, doi:10.5162/SMSI2023/A6.2 (2023)

Busert, S.; Negassi, M.; Scheuerer, A.; Müller, C.; Reiterer, A.
**Modellierung von Gebäuden für Open- und Closed-BIM mithilfe von KI: Erste Konzepte und Ergebnisse des Projekts Kit-CAD**
Allgemeine Vermessungs-Nachrichten AVN 4, 122-131 (2023)

Deliktas, T.; Liewald, M.; Clauß, P.; Kuntz, I.; Schmid-Schirling, T.; Feurer, M.; Dimitropoulos, G.; Wientapper, F.; Räuchle, F.
**Kontrolle und Identifizierung von Pressteilen im freien Fall: Digitalisierung beim Kaltfließpressen durch Freifallinspektion und -kontrolle**
wt Werkstattstechnik 113, 389-394 (2023)

Emperhoff, S.; Eberl, M.; Barraza, J. P.; Brandl, F.; Wöllenstein, J.
**Differential Thermal Conductivity Hydrogen Sensor**
SMSI Sensor and Measurement Science International, doi:10.5162/SMSI2023/A5.3 (2023)

Engel, L.; Schmitt, K.; Wöllenstein, J.
**Colorimetric Detection of Oxygen in Food Packaging**
SMSI Sensor and Measurement Science International, doi:10.5162/SMSI2023/B1.2 (2023)

Gangelhoff, J.; Olshausen, P. von; Frey, S.; Reiterer, A.
**A lightweight laser scanner for UAV-based applications**
Optical Measurement Systems for Industrial Inspection. Proceedings of SPIE 12618, 126181B (2023)

Gangelhoff, J.; Werner, C.; Reiterer, A.
**Lightweight dual-wavelength bathymetric LiDAR for accurate seabed mapping**
Multimodal Sensing and Artificial Intelligence - Technologies and Applications. Proceedings of SPIE 12621, 126210I (2023)

Gaßner, S.; Essing, S.; Tumpold, D.; Schmitt, K.; Wöllenstein, J.
**Miniaturized SMD-Reflow-Capable Photoacoustic $CO_2$-Sensor Using a Dual-Chamber Approach**
SMSI Sensor and Measurement Science International, doi:10.5162/SMSI2023/E7.1 (2023)

Geissler, J.; Rathmann, L.; Weiler, M.
**Combining Daily Sensor Observations and Spatial LiDAR Data for Mapping Snow Water Equivalent in a Sub-Alpine Forest**
Water Research 59, e2023WR034460 (2023)

Groß, H.; Groeneveld, D.; Poschmann, M.; Schürmann, U.; König, J.; Bensch, W.; Wöllenstein, J.; Kienle, L.
**About the Impact of Defect Phases on the Thermoelectric Properties of $Cr_3S_{4-x}Se_x$**
Advanced Engineering Materials 25, 2201505 (2023)

Hauer, B.; Dorfschmidt, A. D.; Münch, F.; Scherer, J.; Carl, D.
**An infrared optical sensor for quantitative inline inspection of nanocoatings on plastic products**
Optical Measurement Systems for Industrial Inspection. Proceedings of SPIE 12618, 126181L (2023)

Herr, S.; Tanaka, H.; Breunig, I.; Bickermann, M.; Kühnemann, F.
**Fanout periodic poling of $BaMgF_4$ crystals**
Optical Materials Express 13, 2158-2164 (2023)

Jäkel, J.-I.; Gölzhäuser, P.: Schmitt, A.; Bange, J.; Klemt-Albert, K.; Reiterer, A.; Marx, S.
**Teilautomatisierte Generierung von digitalen Infrastrukturmodellen mittels Multi-Datenfusion**
Bautechnik 100, 667-673 (2023)

Kammel, F.; Rathmann, L.; Schmitt, A.; Reiterer, A.
**Combining multispectral UAV-borne and terrestrial point cloud data for time-saving forest inventory using artificial intelligence**
Multimodal Sensing and Artificial Intelligence – Technologies and Applications. Proceedings of SPIE 12621, 1262117 (2023)

Kappert, H.; Schopferer, S.; Saeidi, N.; Döring, R.; Ziesche, S.; Olowinsky, A.; Naumann, F.; Jägle, M.; Spanier, M.; Grabmaier, A.
**Sensor Systems for Extremely Harsh Environments**
IMAPSource Proceedings(HiTEN), doi:10.4071/001c.89680 (2023)

Kellner, M.; Stahl, B.; Reiterer, A.
**Reconstructing Geometrical Models of Indoor Environments Based on Point Clouds**
Remote Sensing 15, 4421 (2023)

Khatyreva, A.; Kuntz, I.; Schmid-Schirling, T.; Brox, T.; Carl, D.
**Unsupervised anomaly detection for industrial manufacturing using multiple perspectives of free falling parts**
Automated Visual Inspection and Machine Vision. Proceedings of SPIE 12623, 126230F (2023)

Kunz, J.; Lindner, C.; Herr, S.; Wolf, S.; Kießling, J.; Kühnemann, F.
**Fourier-Transform Mid-Infrared Spectroscopy Using Nonlinear Interferometers**
Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC), doi:10.1109/CLEO/Europe-EQEC57999.2023.10232584 (2023)

Kunz, J.; Lindner, C.; Herr, S.; Wolf, S.; Kießling, J.; Kühnemann, F.
**High resolution Fourier-transform mid-infrared spectroscopy using nonlinear interferometers**
Quantum Sensing, Imaging, and Precision Metrology. Proceedings of SPIE 12447, 124471A (2023)

Lambrecht, A.; Bolwien, C.; Fuhr, H.; Sulz, G.; Isserstedt-Trinke, A.; Magi, A.; Biermann, S.; Wöllenstein, J.
**Compact silicon-based attenuated total reflection (ATR) sensor module for liquid analysis**
Journal of Sensors and Sensor Systems 12, 123 (2023)

Laskin, G.; Seyler, T.; Fratz, M.; Bertz, A.; Carl, D.
**Extended Unambiguous Measurement Range in Multi-Wavelength Digital Holography Using Virtual CAD Rendered Height Maps**
Digital Holography and Three-Dimensional Imaging. Proceedings Optica Imaging Congress, JTu4A.18 (2023)

Laux, P.; Schiller, A.; Bertz, A.; Carl, D.; Reichelt, S.
**Surface roughness measurement of large areas with high spatial resolution by spectral speckle correlation**
Optical Measurement Systems for Industrial Inspection. Proceedings of SPIE 12618, 126181F (2023)

Lindner, C.; Kunz, J.; Herr, S.; Kießling, J.; Wolf, S.; Kühnemann, F.
**High-sensitivity quantum sensing with pump-enhanced spontaneous parametric down-conversion**
APL Photonics 8, 051301 (2023)

Lyu, X.; Gao, H.; Diehle, P.; Altmann, F.; Schmitt, K.; Tarantik, K.; Wöllenstein, J.
**Towards Low Temperature Operation of Catalytic Gas Sensors: Mesoporous $Co_3O_4$-Supported Au-Pd Nanoparticles as Functional Material**
Nanomaterials 13, 2192 (2023)

Lyu, X.; Yurchenko, O.; Diehle, P.; Altmann, F.; Wöllenstein, J.; Schmitt, K.
**Accelerated Deactivation of Mesoporous $Co_3O_4$-Supported Au-Pd Catalyst through Gas Sensor Operation**
Chemosensors 11, 271 (2023)

Merkle, D.; Reiterer, A.
**Automated Method for SLAM Evaluation in GNSS-Denied Areas**
Remote Sensing 15, 5141 (2023)

Merkle, D.; Solass, J.; Schmitt, A.; Rosin, J.; Reiterer, A.; Stolz, A.
**Semi-automatic 3D crack map generation and width evaluation for structural monitoring of reinforced concrete structures**
Journal of Information Technology in Construction 28, 774-805 (2023)

Mönch, S.; Bartholome, K.
**Spatio-temporal solid-state electrocaloric effect exceeding twice the adiabatic temperature change**
Journal of Physics: Energy 5, 045001

Mönch, S.; Reiner, R.; Mansour, K.; Waltereit, P.; Basler, M.; Quay, R.; Molin, C.; Gebhardt, S.; Bach, D.; Binninger, R.; Bartholome, K.
**A 99.74% Efficient Capacitor-Charging Converter using Partial Power Processing for Electrocalorics**
IEEE Journal of Emerging and Selected Topics in Power Electronics 11, 4491-4507 (2023)

Mönch, S.; Reiner, R.; Waltereit, P.; Basler, M.; Quay, R.; Gebhardt, S.; Molin, C.; Bach, D.; Binninger, R.; Bartholome, K.
**How highly efficient power electronics transfers high electrocaloric material performance to heat pump systems**
MRS Advances 8, 787-796 (2023)

Mrokon, A.; Kirste, L.; Buse, K.; Breunig, I.
**Potassium Tantalate-Niobate for Electro-Optically Driven Adiabatic Frequency Conversion**
Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC), doi:10.1109/CLEO/EUROPE-EQEC57999.2023.10231964 (2023)

Pannek, C.
**Werkstoffe und Sensoren für die Wasserstoffinfrastruktur**
gwf. Gas + Energie 164(2-3), 42-43 (2023)

Pannek, C.; Lambrecht, A.; Wöllenstein, J.; Buse, K.; Keßler, A.; Tschuncky, R.; Jäckel, P.; Quiring, S.; Youssef, S.; Herrmann, H.-G.; Oeckl, S.
**Sensors and safety**
In: Neugebauer, R. (Ed.) Hydrogen Technologies. Springer, Cham. 357-391 (2023)

Placke, M.; Lindner, C.; Kviatkovsky, I.; Chrzanowski, H. M.; Kühnemann, F.; Ramelow, S.
**Fourier-transform mid-IR hyperspectral imaging with undetected photons**
Conference on Lasers and Electro-Optics, CLEO, AM2N.4 (2023)

Poku-Agyemang, K. N.; Kellner, M.; Schmitt, A.; Reiterer, A.
**Creating 3D Models of Bridges Using Different Data Sources and Machine Learning Methods 33rd European Safety and Reliability Conference, ESREL. Proceedings, 3020-3025 (2023)**

Poku-Agyemang, K. N.; Reiterer, A.
**3D Reconstruction from 2D Plans Exemplified by Bridge Structures**
Remote Sensing 15, 677 (2023)

Riexinger, G.; Regina, D. J.; Haar, C.; Schmid-Schirling, T.; Landwehr, I.; Seib, M.; Lips, J.; Fehrenbach, S.; Stübing, J.; Carl, D.; Sauer, A.
**Traceability in Battery Production: Cell-Specific Marker-Free Identification of Electrode Segments**
Stuttgart Conference on Automotive Production 2022. Proceedings, 344-353 (2023)

Schiller, A.; Fratz, M.; Seyler, T.; Bertz, A.; Carl, D.
**Multiwavelength Holography: Absolute Height Measurements Ready for Application in Gear Metrology**
Digital Holography and Three-Dimensional Imaging. Proceedings Optica Imaging Congress, HM2C.5 (2023)

Schipper, J.; Bach; D.; Mönch, S.; Molin, C.; Gebhardt, S.; Wöllenstein, J.; Schäfer-Welsen, O.; Vogel, C.; Langebach, R.; Bartholome, K.
**On the efficiency of caloric materials in direct comparison with exergetic grades of compressors**
Journal of Physics: Energy 5, 045002

Schlosser, M.; Tichelmann, S.; Schäffner, D.; Ohl de Mello, D.; Hambach, M.; Schütz, J.; Birkl, G.
**Scalable Multilayer Architecture of Assembled Single-Atom Qubit Arrays in a Three-Dimensional Talbot Tweezer Lattice**
Physical Review Letters 130, 180601(2023)

Schmid-Schirling, T.
**Im freien Fall**
Quality Engineering 2, 44-46 (2023)

Schmid-Schirling, T.; Saum, N.; Eberz, C.
**Marker-Free, Single Item Traceability in Gear Wheel Production Based on Inherent Surface Patterns**
VDI Berichte 2422, 1877-1888 (2023)

Schmieder, L.; Koss, P.; Kühnemann, F.
**Magnetic Flow Metering with Optically Pumped Magnetometers (OPM)**
SMSI Sensor and Measurement Science International. Proceedings, 69-70 (2023)

Schmitt, K.; Sendelbach, M.; Weber, C.; Wöllenstein, J.; Strahl, T.
**Resonant photoacoustic cells for laser-based methane detection**
Journal of Sensors and Sensor Systems 12, 37-44 (2023)

Schwegler, M.; Müller, C.; Reiterer, A.
**Integrated Gradients for Feature Assessment in Point Cloud-Based Data Sets**
Algorithms 16, 316 (2023)

Seyler, T.; Fratz, M.; Schiller, A.; Bertz, A.; Carl, D.; Schmitt-Manderbach, T.; Langer, M.
**Digital holography in a machine tool: Measuring large-scale objects with micron accuracy**
Optical Measurement Systems for Industrial Inspection. Proceedings of SPIE 12618, 126181U (2023)

Stiefvater, G.; Hespos, Y.; Wiedenmann, D.; Lambrecht, A.; Brunner, R.; Wöllenstein, J.
**A Portable Laser Spectroscopic System for Measuring Nitrous Oxide Emissions on Fertilized Cropland**
Sensors 23, 6686 (2023)

Stober, I.; Jägle, M.; Kohl, T.
**Optimizing scenarios of a deep geothermal aquifer storage in the southern Upper Rhine Graben**
Geothermal Energy 1, 34 (2023)

Störk, T.; Seyler, T.; Bertz, A.; Carl, D.
**Investigation of Permuted Phase Steps on Multiwavelength Digital Holographic Measurements**
Digital Holography and Three-Dimensional Imaging. Proceedings Optica Imaging Congress, HTu2C.5 (2023)

Strahl, T.; Steinebrunner, J.; Weber, C.; Wöllenstein, J.; Schmitt, K.
**Photoacoustic methane detection inside a MEMS microphone**
Photoacoustics 29, 100428 (2023)

Teicht, C.; Winkler, M.
**Neue Konzepte zum regelbaren Wärmetransport: Heatpipe-basierte Wärmeschalter für Energiesysteme**
BWK Energie 75(5-6), 47-49 (2023)

Thiemann, K.; Blug, A.; Bertz, A.
**Quantum Magnetometry for Material Testing**
SMSI Sensor and Measurement Science International. Proceedings, 73-74 (2023)

Thiemann, K.; Blug, A.; Bertz, A.; Carl, D.
**Demonstration of an OPM flux guide scanner for high-resolution magnetic non-destructive testing**
Photonics for Quantum. Proceedings of SPIE 12633, 1263309 (2023)

Unmüßig, S.; Bach, D.; Nouchokgwe Kamgue, Y. D.; Defay, E.; Bartholome, K.
**Phenomenological Material Model for First-Order Electrocaloric Material**
Energies 16, 5837 (2023)

Vierhub-Lorenz, V.; Gangelhoff, J.; Werner, C.; Bett, C. M.; Frenner, K.; Osten, W.; Reiterer, A.
**Development of a LiDAR system for low visibility conditions**
Optical Measurement Systems for Industrial Inspection. Proceedings of SPIE 12618, 126181A (2023)

Vierhub-Lorenz, V.; Werner, C.; Olshausen, P. von; Reiterer, A.
**Optischer Hammerschlagtest – neue Technologien für die Tunnelinspektion**
EI – Der Eisenbahningenieur 74(10), 18-21 (2023)

Vierhub-Lorenz, V.; Werner, C.; Olshausen, P. von; Reiterer, A.
**Towards Automating Tunnel Inspections with Optical Remote Sensing Techniques**
AVN Allgemeine Vermessungs-Nachrichten 130(1-2), 35-41 (2023)

Vierhub-Lorenz, V.; Werner, C.; Weiher, K.; Heinze, C.; Reiterer, A.
**Laser-based measurement system for the detection of delamination in tunnel linings**
Optical Measurement Systems for Industrial Inspection. Proceedings of SPIE 12618, 1261824 (2023)

Wang, H.; Laskin, G.; He, W.; Boschker, H.; Yi, M.; Braun, W.; Fenk, B.; Srot, V.; Mannhart, J.; Aken, P. A. van
**Lattice Anisotropy, Oxygen Octahedral Rotation and Tunable Magnetic Anisotropy in Patterned $SrRuO_3$ Quantum Structures**
Microscopy and Microanalysis 29(Suppl. 1), 1650 (2023)

Weber, C.; Kapp, J.; Wöllenstein, J.; Schmitt, K.
**Novel approach for efficient resonance tracking in photoacoustic gas sensor systems based on a light-induced wall signal**
Photoacoustics 31, 100495 (2023)

Weber, P.-K.; Santos, P.; Rentschler, L.; Fuchs, T.; Bauer, M.; Friederich, F.; Jelen, E.; Drezen, E. L.; Rauch, T.; Jelito, V.; Erdogmus, C.; Humanicka, W.

**Digital Twins, Damage Detection and Material Analysis**

in: Pollmer, U. (Ed.) Fraunhofer Technologies for Heritage Protection in Times of Climate Change and Digitization. IRB Verlag, Stuttgart. 22-63 (2023)

Werner, C.; Frey, S.; Reiterer, A.

**Automated visual vegetation detection for weed management on transportation infrastructure**

Automated Visual Inspection and Machine Vision. Proceedings of SPIE 12623, 126230G (2023)

Werner, C.; Gangelhoff, J.; Frey, S.; Steiger, D.; Reiterer, A.

**Development of a compact pulsed time-of-flight LiDAR platform for underwater measurements**

International Hydrographic Review 29, 200-2027 (2023)

Winkler, M.; Vergez, M.; Mahlke, A.; Gebauer, M.; Müller, P.; Reising, C.; Bartholome, K.; Schäfer-Welsen, O.

**Flat-Plate PHP with Gravity-Independent Performance and High Maximum Thermal Load**

Energies 16, 7463 (2023)

Wolf, S.; Lindner, C.; Trendle, T.; Kießling, J.; Kühnemann, F.

**Time-resolved photothermal breath analysis**

Quantum Sensing and Nano Electronics and Photonics. Proceedings of SPIE 12430, 124300 (2023)

Wolf, S.; Lindner, C.; Trendle, T.; Kießling, J.; Wöllenstein, J.; Kühnemann, F.

**Breath-Resolved Monitoring of Metabolic Trace Gases with Photothermal Spectroscopy**

Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC), doi:10.1109/CLEO/Europe-EQEC57999.2023.10231906

Wöllenstein, J.; Reindl, L. M.

**Themenheft Sensoren und Messsystem 2022**

tm – Technisches Messen 90, 353-354 (2023)

Yassine, H.; Weber, C.; Brugger, N.; Wöllenstein, J.; Schmitt, K.

**Towards a Miniaturized Photoacoustic Detector for the Infrared Spectroscopic Analysis of $SO_2F_2$ and Refrigerants**

Sensors 23, 180 (2023)

Yassine, H.; Weber, C.; Wöllenstein, J.; Schmitt, K.

**Evaluation of Photoacoustic Detectors for Methyl Bromide Sensing**

SMSI Sensor and Measurement Science International. Proceedings, 157-158 (2023)

Yurchenko, O.; Pernau, H.-F.; Engel, L.; Wöllenstein, J.

**Differential thermal analysis techniques as a tool for preliminary examination of catalyst for combustion**

Scientific Reports 13, 9792 (2023)

# **Reports** 2023

Yurchenko, O.; Bierer, B.; Wöllenstein, J.

MEMS-basierte katalytische Sensoren für brennbare Gase (E! 113779 Mescal); Sub-project: Entwicklung und Herstellung von neuen katalytisch-aktiven Materialien zur Methandetektion

Final report; Reporting period: 01.07.2020 – 31.12.2022
Freiburg/Brsg., 2023, pp. 24

Schmid-Schirling, T.; Eberz, C.

Markierungsfreie Rückverfolgung des gefällten Baumstamms von der Ernte bis ins Sägewerk (DiGeBaSt)

Final report; Reporting period: 01.04.2021 – 31.03.2023
Freiburg/Brsg., 2023, pp. 29

Fratz, M.; Schiller, A.; Bertz, A.

Dynamisch-holographisches Messverfahren zur Erfassung metallischer Freiformflächen (HoloMotion)

Final report; Reporting period: 01.02.2017 – 31.01.2023
Freiburg/Brsg., 2023, pp. 25

# **Granted patents** 2023

Dimopoulos, N.; Höfler, H.; Reiterer, A.; Wölfelschneider, H.
Apparatus for capturing superimposed distance and intensity images
AT525126B1

Bartholomé, K.; Horzella, J.; König, J.; Mahlke, A.; Vergez, M.
Method and apparatus for operating cyclic process-based systems
EP3387337B1

Beckmann, T.; Fratz, M.; Schiller, A.
Method and device for interferometric measurement of a surface of a moving specimen
EP3581879B1

Brandenburg, A.; Blättermann, A.; Schütz, J.
Method and device for classifying particulate contamination on a surface
EP3754324B1

Beckmann, T.; Seyler, T.
Method for generating information from at least one camera image
EP3855390B1

Beckmann, T.; Seyler, T.
Method and apparatus for producing information from a camera image
US11568528B2

Anders, J.; Basler, C.; Bertz, A.; Seyler, T.
Interferometer for digital interferometry or digital holography, using a deflecting mirror
EP3855111B1

Herr, S.
Method and device for generating electromagnetic useful beam
EP3985808B1

Schmitt, K.; Weber, C.; Wöllenstein, J.; Bittner, A.; Dehe, A.
Photoacoustic spectroscopy of gas mixtures by means of tunable Fabry-Perot interferometer
EP3919890B1

Kießling, J.; Kühnemann, F.; Trendle, T.; Wolf, S.
Method and Sensor for the photothermal determination of absorption of electromagnetic excitation radiation in a sample
EP4080197B1

# **Doctoral Theses** 2023

Bachmann, N.; Koch, T. [Reviewer]

**Steigerung der Systemperformance eines elastokalorischen Kühlsystems**

[Karlsruhe, TU., Diss., 2023]
Berlin, Logos Verlag. Forschungsberichte aus dem Institut für Kolbenmaschinen 1/2024 (2024)

Gassner, S.; Wöllenstein, J. [Reviewer]

**Miniaturisierter $CO_2$-Sensor mit wafer-gebondetem photoakustischen MEMS-Detektor**

[Freiburg, Univ., Diss., 2023]
Aachen, Shaker-Verlag. Gas Sensors 16 (2024)

Minet, Y.; Buse, K. [Reviewer]

**Elektro-optisch abstimmbare Lichtquellen mittels Lithiumniobat-Flüstergalerieresonatoren**

[Freiburg, Univ., Diss., 2023]

Zschiesche, K. E.; Reiterer, A. [Reviewer]

**Methods and algorithms of an imaging total station**

[Freiburg, Univ., Diss., 2023]
Freiburg, FreiDoc plus, urn:nbn:de:bsz:25-freidok-2407627

# **Large-scale projects 2023** Funded by the public sector

In 2023, our scientists worked on twelve publicly funded research projects amounting to more than one million euros in volume for Fraunhofer IPM.

**HOLOMOTION** Dynamic holographic measurement technique for mapping freeform metal surfaces / Sub-project: Researching a method for performing interferometric measurements in motion – dynamic holography
Duration: February 1, 2017 – March 31, 2023
Funding: BMBF; Project Management Agency: VDI Technologie-zentrum GmbH

**MultiVIS** University cooperation with Furtwangen University (HFU)
Duration: July 1, 2018 – December 31, 2023
Funding: Fraunhofer-Gesellschaft (cooperation program with Universities of Applied Sciences (UAS)

**QMag** Development of two complementary quantum magnetometers for measuring minuscule magnetic fields with high resolution and sensitivity at room temperature
Duration: March 21, 2019 – December 31, 2023
Funding: Fraunhofer-Gesellschaft (Flagship project)

**LaserBeat** Impact hammer test using light – non-contact full inspection of tunnels on the basis of laser-induced structure-borne sound
Duration: April 1, 2019 – December 31, 2023
Funding: Fraunhofer-Gesellschaft (WISA)

**ElKaWe** Electrocaloric heat pumps
Duration: October 1, 2019 – September 30, 2023
Funding: Fraunhofer-Gesellschaft (Flagship project)

**HochPerForm** Ultra-compact fast actuator technology based on shape-memory alloys
Duration: March 1, 2020 – February 28, 2023
Funding: Fraunhofer-Gesellschaft (PREPARE)

**MIAME** Micrometer to meter: Laser light for 3D measurements on the meter scale with accuracies in the sub-micrometer range
Duration: April 1, 2020 – March 31, 2023
Funding: Fraunhofer-Gesellschaft (PREPARE)

**QTWP** QT waveguide plus: Labor upgrade for LNOI technology and waveguide characterization
Duration: September 1, 2021 – August 31, 2023
Funding: BMBF; Project Management Agency: VDI Technologie-zentrum GmbH

**FMD-QNC** Research Fab Microelectronics Germany (FMD) – Module Quantum and Neuromorphic Computing (FMD-QNC)
Duration: November 1, 2022 – December 31, 2025
Funding: BMBF; Project Management Agency: VDI/VDE-IT

**Bau-DNS** Comprehensive process for sustainable, modular and circular building refurbishment
Duration: January 1, 2023 – December 31, 2026
Funding: Fraunhofer-Gesellschaft (Flagship project)

**CoLiBri** Collaborative LiDAR to monitor infrastructure in the water and at the shoreline
Duration: June 1, 2023 – November 30, 2024
Funding: Fraunhofer-Gesellschaft (IMPULS)

**MultiLambdaChip** Optically-integrated multi-wavelength laser system for holographic 3D surface inspection in industrial quality assurance
Duration: October 1, 2023 – September 30, 2026
Funding: BMBF, Project Management Agency: VDI-Technologie-zentrum GmbH

# **Network** Our partners

**We are actively involved in groups, specialist organizations and networks, within the Fraunhofer-Gesellschaft, nationwide and worldwide.**

## Fraunhofer Group for Light & Surfaces

The Fraunhofer Group for Light & Surfaces brings together the Fraunhofer-Gesellschaft's scientific and technical expertise in the areas of laser, optical, measurement and surface technology. With a total of approximately 1300 employees, the six Fraunhofer Institutes in the Group work together to solve complex, application-oriented customer inquiries at the cutting edge of science and technology. But the Fraunhofer Institutes are not only partners in innovation. They also work to produce new generations of scientific and technical experts. In cooperation with the local universities, the young scientists at the Fraunhofer Institutes bring together academic research and industry.

Chairman of the group is Professor Karsten Buse, the central office is headed by Dr. Heinrich Stülpnagel (Fraunhofer IPM).
light-and-surfaces.fraunhofer.de/en

## Fraunhofer-Gesellschaft

- Fraunhofer Group for Light & Surfaces
- Fraunhofer Agriculture and Food Industry Alliance
- Fraunhofer Building Innovation Alliance
- Fraunhofer Business Area Cleaning
- Fraunhofer Business Unit Vision
- Fraunhofer Transport Alliance

## Germany

- AMA Verband für Sensorik und Messtechnik e.V.
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- Competence Center for Applied Security Technology e. V. (CAST)
- Deutsche Forschungsgesellschaft für Oberflächenbehandlung e.V. (DFO)
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- Deutsche Hydrographische Gesellschaft e. V. (DHyG)
- Deutsche Physikalische Gesellschaft e. V. (DPG)
- Deutsche Thermoelektrik Gesellschaft e. V. (DTG)
- Deutscher Hochschulverband (DHV)
- Deutscher Kälte- und Klimatechnischer Verein e.V. (DKV)
- Draht-Welt Südwestfalen – netzwerkdraht e. V.
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- Gesellschaft Deutscher Chemiker e. V. (GDCh)
- Green City Cluster Freiburg
- Maritimes Cluster Norddeutschland e.V.
- microTEC Südwest e. V.
- Nano-Zentrum Euregio Bodensee e. V. (NEB)
- Photonics BW e. V. – Innovations-Cluster für Optische Technologien in Baden-Württemberg
- Strategische Partner – Klimaschutz am Oberrhein e. V.
- VDI/VDE-Gesellschaft Mess- und Automatisierungstechnik (GMA)
- VDSI – Verband für Sicherheit, Gesundheit und Umweltschutz bei der Arbeit e. V.
- Wissenschaftliche Gesellschaft Lasertechnik e. V .

## International

- European Thermoelectric Society (ETS)
- International Thermoelectric Society (ITS)
- Optica (formerly OSA)

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# The Fraunhofer-Gesellschaft

The Fraunhofer-Gesellschaft, based in Germany, is one of the world's leading applied research organizations. It plays a crucial role in the innovation process by prioritizing research in key future technologies and transferring its research findings to industry in order to strengthen Germany as an economic hub as well as for the benefit of society.

As an important customer group, small- and medium-sized companies in particular tap into Fraunhofer's expertise and resources to develop new technologies and maintain their competitiveness. For years, Fraunhofer has been one of the most active patent applicants in Germany and Europe. The research organization is therefore developing an extensive, international patent portfolio in various technology sectors, primarily as a basis for transferring technology through research projects, spin-offs and licensing. In this way, Fraunhofer experts support industry partners from ideation to market launch, and Fraunhofer's interdisciplinary and international collaboration in specific market environments addresses social objectives in important technology areas. Fraunhofer also promotes research into key technologies that are vital for society as a whole by applying specific, interdisciplinary and international collaboration geared to the needs of the market. Examples include technologies for the energy transition, cybersecurity and underlying models for generative artificial intelligence. Fraunhofer is an attractive and established party for public-private partnerships and also makes a significant contribution to strengthening Germany as a hub for innovation and ensuring its viability in the future. Its activities create jobs in Germany, boost investment effects in the private sector and increase the social acceptance of new technology. International collaboration projects with excellent research partners and companies across the globe ensure that the Fraunhofer-Gesellschaft remains in direct contact with the most prominent scientific communities and economic areas.

Founded in 1949, the Fraunhofer-Gesellschaft currently operates 76 institutes and research units throughout Germany. Its nearly 32,000 employees, predominantly scientists and engineers, work with an annual business volume of 3.4 billion euros; 3.0 billion euros of this stems from contract research, which is divided into three funding pillars. Fraunhofer generates a share of this from industry and license-fee revenue to a sum of 836 million euros. This high proportion of industrial revenue is Fraunhofer's unique selling point in the German research landscape. The importance of direct collaboration with industry and the private sector that this requires ensures a constant push for innovation in the economy, while at the same time strengthening German and European competitiveness.

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# Imprint


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