Fraunhofer
IPM

FRAUNHOFER INSTITUTE FOR PHYSICAL MEASUREMENT TECHNIQUES IPM

2018 2019 ANNUAL REPORT

www.ipm.fraunhofer.de/en

MEASURING · MONITORING · OPTIMIZING

<< Cover *Elastocaloric materials are suitable for the construction of highly efficient heat pumps for heating and cooling – without the need for harmful refrigerants (more on page 78).*

PRODUCTION CONTROL

OBJECT AND SHAPE DETECTION

GAS AND PROCESS TECHNOLOGY

THERMAL ENERGY CONVERTERS

"From quality control to quality creation – measuring makes it possible"

< Prof Dr Karsten Buse, Executive Director.

Dear customers and partners,

Measurement technology is utilized in industrial production to help ensure product quality in a number of ways. Semi-finished products and components are checked for defects as early as the manufacturing phase, in order to avoid faults in larger assembled devices later on. In our Production Control department, we are developing 3D and 2D measurement systems capable of inspecting components extremely quickly and precisely. The systems can identify the shape and surface characteristics of complex components with up to 100 million 3D measuring points per second. Based on these measurements, faulty parts can be identified and then recycled or reworked and inspected once again.

Many measurement techniques have improved so much in the last few years, in terms of speed and robustness, that measurements are no longer just isolated assessments to be completed after production, but can be carried out during. Elaborate control loops enable modern inline measurement technologies to compensate for production fluctuations – caused by tool wear, material variations or climatic influences, for example – during the production process itself. This makes measurement systems a part of process control. Quality assurance becomes a part of production. It is no longer quality control, but quality creation.

Some impressive examples include a digital holographic 3D measurement system developed by us, which measures workpieces with micrometer precision whilst they are being machined, as well as an inline sensor which identifies minuscule chips or particles on components so that they can be removed prior to further processing.

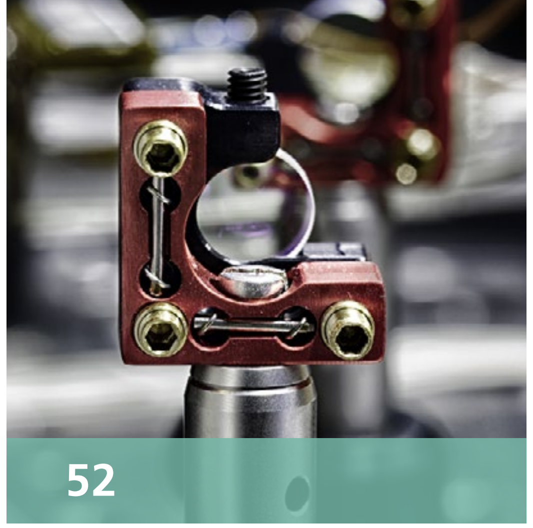
As such improvements reduce waste, save resources and increase throughput, companies often achieve returns on their investments after only a few months, even for expensive measurement systems. Thanks to process control, the full potential of the machines can be harnessed. Inline measurement technology is becoming increasingly important in industrial production as a result, which is further raising the demands on measurement systems. This does not only require excellent technology, but also measurement techniques with a level of reliability and availability which is neither achieved by nor expected from laboratory equipment or near-line devices. In light of this, we have recently established standards for software development and testing in particular which further reduce the breakdown risk for our systems.

The trend of optimizing processes through a combination of both more and better measurement techniques is also visible in our other specialist departments. Measuring the calorific value of gases while they are being fed through the pipeline makes it possible to control incinerators more precisely. Capturing 3D images of infrastructure enables us to plan routes for the expansion of the fiber-optic network much more efficiently than before. We can also seamlessly monitor district heating pipelines using optical measurement techniques.

On the following pages, you will read about what measurement technology is capable of, how versatile it is and just how imaginatively our scientists are implementing their knowledge in ready-to-use systems. These include depth-resolved material analyses using ultrashort light pulses, multi-color and underwater laser scanners, color-changing sensors for fire gas detection, thermal sensors and much more.

I very much hope you enjoy browsing through our annual report and discovering our innovations.

Yours, Karsten Buse



CONTENTS

ORGANIZATION

MANAGEMENT

Director
Prof Dr Karsten Buse
P +49 761 8857-111
karsten.buse@ipm.fraunhofer.de

Deputy Director
Dr Daniel Carl
P +49 761 8857-549
daniel.carl@ipm.fraunhofer.de

EXECUTIVE ASSISTANTS AND PUBLIC RELATIONS

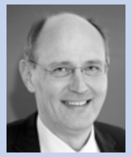
Science Management
Dr Rosita Sowade
P +49 761 8857-222
rosita.sowade@ipm.fraunhofer.de

Organizational Development
Dr Heinrich Stülpnagel
P +49 761 8857-269
heinrich.stuelpnagel@ipm.fraunhofer.de

Communications and Media
Holger Kock
P +49 761 8857-129
holger.kock@ipm.fraunhofer.de

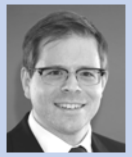
PRODUCTION CONTROL

Head of Department
Dr Daniel Carl
P +49 761 8857-549
daniel.carl@ipm.fraunhofer.de



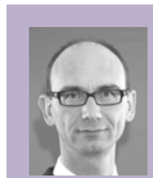
Optical Surface Analytics
Dr Albrecht Brandenburg
P +49 761 8857-306
albrecht.brandenburg@ipm.fraunhofer.de

Inline Vision Systems
Dr Tobias Schmid-Schirling
P +49 761 8857-281
tobias.schmid-schirling@ipm.fraunhofer.de



Geometrical Inline Measurement Systems
Dr Alexander Bertz
P +49 761 8857-362
alexander.bertz@ipm.fraunhofer.de

OBJECT AND SHAPE DETECTION



Head of Department
Prof Dr Alexander Reiterer
P +49 761 8857-183
alexander.reiterer@ipm.fraunhofer.de

Mobile Terrestrial Scanning
Prof Dr Alexander Reiterer
P +49 761 8857-183
alexander.reiterer@ipm.fraunhofer.de

Airborne and Underwater Scanning
Simon Stemmler
P +49 761 8857-211
simon.stemmler@ipm.fraunhofer.de

Smart Data Visualization
Prof Christoph Müller
P +49 761 8857-236
christoph.mueller@ipm.fraunhofer.de

GAS AND PROCESS TECHNOLOGY

Head of Department
Prof Dr Jürgen Wöllenstein
P +49 761 8857-134
juergen.woellenstein@ipm.fraunhofer.de

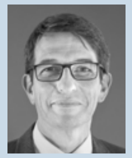
Integrated Sensor Systems
Dr Marie-Luise Bauersfeld
P +49 761 8857-290
marie-luise.bauersfeld@ipm.fraunhofer.de

Spectroscopy and Process Analytics
Dr Raimund Brunner
P +49 761 8857-310
raimund.brunner@ipm.fraunhofer.de

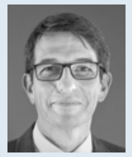
Thermal Measurement Techniques and Systems
Martin Jägle
P +49 761 8857-345
martin.jaegle@ipm.fraunhofer.de

Nonlinear Optics and Quantum Sensing
Dr Frank Kühnemann
P +49 761 8857-457
frank.kuehnemann@ipm.fraunhofer.de

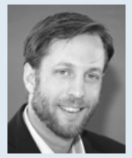
THERMAL ENERGY CONVERTERS



Head of Department
Dr Olaf Schäfer-Welsen
P +49 761 8857-173
olaf.schaefer-welsen@ipm.fraunhofer.de



Thermoelectric Systems
Dr Olaf Schäfer-Welsen
P +49 761 8857-173
olaf.schaefer-welsen@ipm.fraunhofer.de



Caloric Systems
Dr Kilian Bartholomé
P +49 761 8857-238
kilian.bartholome@ipm.fraunhofer.de

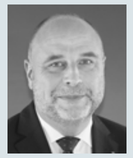
TECHNICAL SERVICES

Head of Technical Services
Clemens Faller
P +49 761 8857-214
clemens.faller@ipm.fraunhofer.de

Mechanics and Construction
Thomas Hinrichs
P +49 761 8857-254
thomas.hinrichs@ipm.fraunhofer.de

Facility Management
Clemens Faller
P +49 761 8857-214
clemens.faller@ipm.fraunhofer.de

ADMINISTRATION AND IT



Head of Administration
Wolfgang Oesterling
P +49 761 8857-120
wolfgang.oesterling@ipm.fraunhofer.de

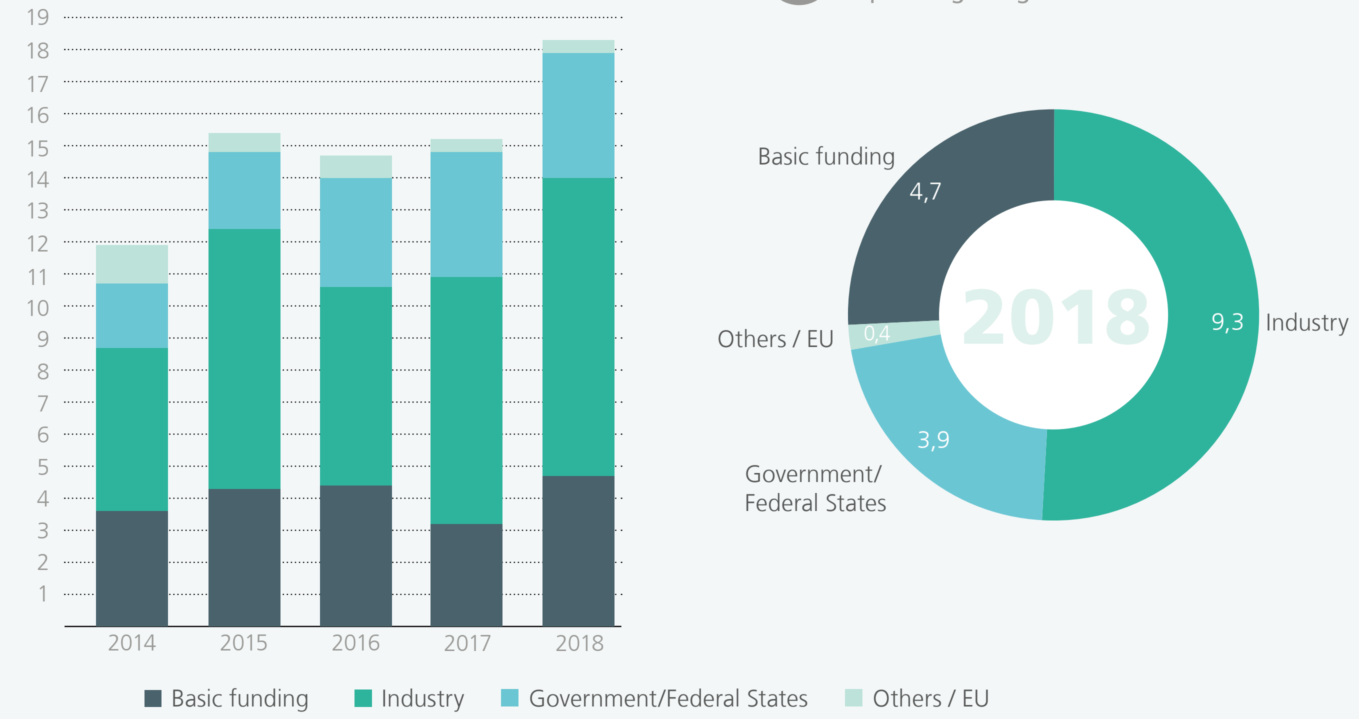
Administration
Sabine Gabele
P +49 761 8857-159
sabine.gabele@ipm.fraunhofer.de

Information and Communications Technology
Gerd Kühner
P +49 761 8857-226
gerd.kuehner@ipm.fraunhofer.de

Human Resources
Anneliese Zwölfer
P +49 761 8857-116
anneliese.zwoelfer@ipm.fraunhofer.de

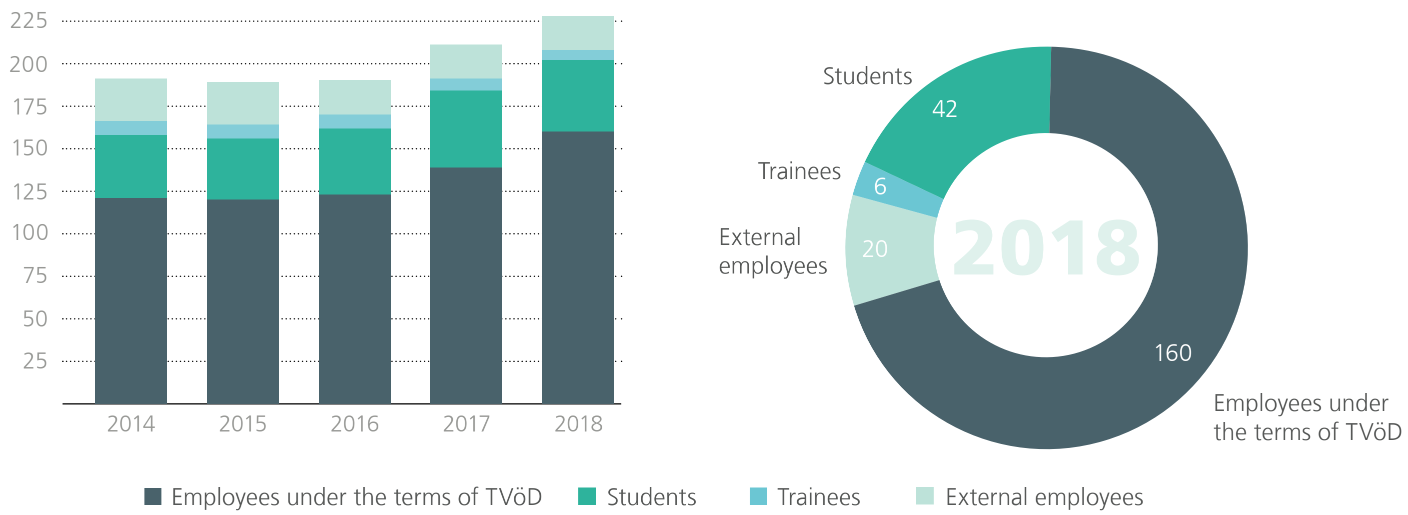
Operating budget in million euros

18,3 million
Operating budget



Personnel

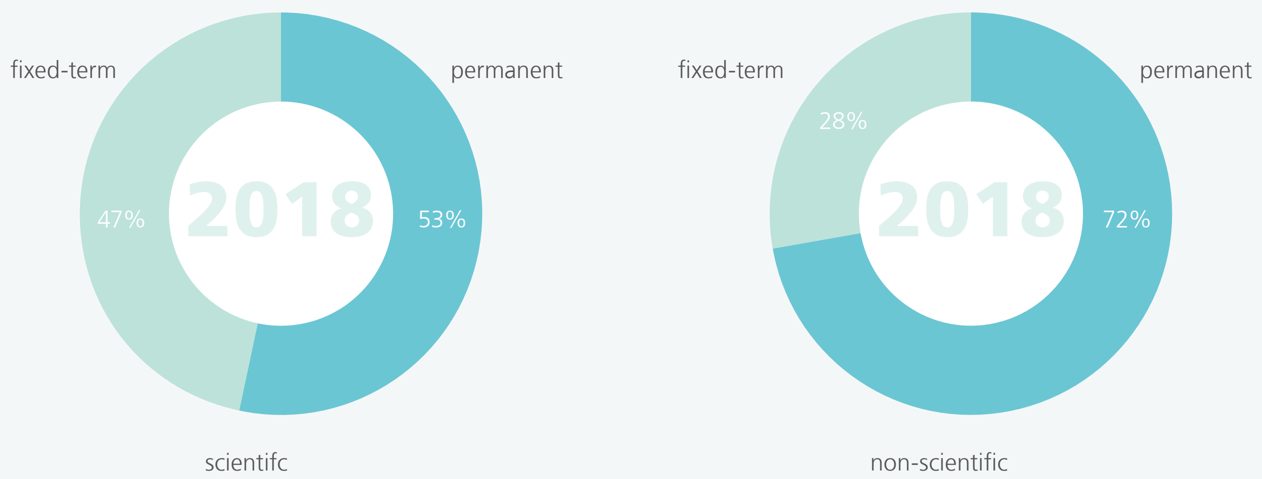
228
Employees



OUR ADVISORY BOARD

A distinguished and dedicated board of trustees advises and supports the institute in strategic issues and decisions for the future.

Staff under the terms of the Collective Agreement for the Public Service TVöD: percentages of fixed-term/permanent contracts of employment



< The new "Hermle C250" weighs in at ten metric tons. Extreme precision was needed to deliver and position it in the workshop.

INVESTMENT IN TECHNICAL EQUIPMENT

Fraunhofer IPM invested more than one million euros in large devices and machines that were commissioned during the 2018 annual period.

5-axis milling machine (Hermle C250)
The new C250 "dynamic machining center" from Hermle brings the total of available milling machines to five.
- Increased manufacturing capacity and flexibility
- Higher precision
- Easier handling thanks to zero-point clamping system

Vacuum FTIR spectrometer (Bruker VERTEX 80/80v)
An ultra modern Fourier transform infrared spectrometer replaces several other – in some cases obsolete – spectrometers.
- Powerful device for broadband spectroscopy
- High degree of stability, resolution, and sensitivity

Semiautomated UV nanoimprint lithography system
Within the field of nano- and microsystems engineering, functional materials and surfaces for micro-optical applications, miniaturized gas sensors, thermal sensors, and energy converters are manufactured using the new lithography system.
- Double-sided structuring of flexible substrates, including special geometries
- Critical dimensions down to nanometer scale
- "Surface micromachining", shaping 3D surfaces with large aspect ratios

Optical reference measurement system, Leica Absolute Tracker AT960 incl. T-Scan and T-Probe
Thanks to the new laser tracker, we now have a multifunctional reference system for inspecting and calibrating our laser scanners.
- Rapid inspection and calibration of measurement systems and measuring apparatuses, even for large measurement volumes
- Full automation of calibration processes
- Ultimate precision when measuring distances and angles
- Flexible use (incl. outside the lab) thanks to small design

Dual-comb spectrometer
Spectrometers that use frequency combs represent a new class of powerful tools in spectroscopy and analytics. They combine the advantages of Fourier transform spectroscopy and tunable infrared lasers.
- High levels of coherence make long measurement distances viable for high sensitivity analytics
- Wide spectral coverage enables analysis of complex mixtures
- Reference system for developing new application scenarios for clients

LARGE-SCALE PROJECTS 2018

A total of eleven research projects with a volume of more than one million euros allocated to Fraunhofer IPM were carried out at the Institute in 2018. Two of the major projects were completed in 2018.

Freifall
100 percent quality testing of semi-finished parts by geometry and surface analysis in free fall
Project duration: 4/1/2017–3/31/2020
Funding: Fraunhofer-Gesellschaft

DeepInspect
3D-capture and monitoring of underwater structures
Project duration: 4/01/2015–12/31/2018
Funding: Fraunhofer-Gesellschaft

MultiVIS
Cooperation with Hochschule Furtwangen University HFU
Project duration: 7/01/2018–12/31/2023
Funding: Fraunhofer-Gesellschaft

TOXIG
Color change based sensors for toxic gas detection
Project duration: 3/01/2017–8/31/2020
Funding: Fraunhofer-Gesellschaft

eHarsh
Sensor systems for extremely harsh environments
Project duration: 7/01/2017–12/31/2020
Funding: Fraunhofer-Gesellschaft (Lighthouse project)

QUILT
Quantum Methods for Advanced Imaging Solutions
Project duration: 9/01/2017–8/31/2020
Funding: Fraunhofer-Gesellschaft (Lighthouse project)

FluMEMS
MEMS based catalytic thermal sensors for gas and liquid detection
Project duration: 4/1/2018–3/31/2021
Förderung: Fraunhofer-Gesellschaft

thermoHEUSLER 2
Systems integration for thermoelectric exhaust gas waste heat recovery
Project duration: 6/01/2015–11/30/2018
Funding: BMWi
Project executing organization: TÜV Rheinland Consulting GmbH

MagCon
Magnetocalorics: Development of coolant-free, highly efficient heat pumps for heating and cooling
Project duration: 2/01/2016–9/30/2019
Funding: Fraunhofer-Gesellschaft

MagMed
Development of a coolant-free, efficient cooling technology, sub-project: System development and measurement technology
Project duration: 6/01/2017–5/31/2020
Funding: BMWi,
Project executing organization: Forschungszentrum Jülich GmbH

Elasto-Cool
Elastocalorics: Development of highly efficient heat pumps for cooling and heating without the need for harmful coolants
Project duration: 8/01/2018–7/31/2020
Funding: BMBF,
Project executing organization: VDI/VDE Innovation und Technik GmbH

> The Faculty of Engineering campus at the University of Freiburg. Fraunhofer IPM's new building is under construction close by.

PROFESSORSHIPS AT UNIVERSITIES AND UNIVERSITIES OF APPLIED SCIENCES

Fraunhofer IPM maintains connections with the University of Freiburg in the form of three associated professorships. Through the close university connection, we can draw on latest results from basic research in our project work. Since February 2019, the institute has also been cooperating with the Furtwangen University of Applied Sciences (HFU). As part of the Fraunhofer-University Cooperation Program, Professor Christoph Müller from the Faculty of Digital Media will lead the newly established working group "Smart Data Visualization SDV" at Fraunhofer IPM. The five-year cooperation provides an insight into the application-oriented research of the HFU.

ALBERT-LUDWIGS-UNIVERSITÄT FREIBURG

Department of Microsystems Engineering – IMTEK

Laboratory for Optical Systems
Prof Dr Karsten Buse

Research foci
- Nonlinear optical materials
- Optical whispering gallery resonators
- Miniature solid-state lasers
- Optical frequency converters (optical parametric oscillators OPO)
- Frequency combs
- Fast tuning of laser frequencies
- Integrated optics

Laboratory for Gas Sensors
Prof Dr Jürgen Wöllenstein

Research foci
- Micro structured gas sensors
- Micro structured IR emitters for the mid infrared 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

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

FURTWANGEN UNIVERSITY

Faculty of Digital Media

Professorship of Computer Graphics
Prof Christoph Müller

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

PROFESSOR KARSTEN BUSE BECOMES FELLOW OF THE OPTICAL SOCIETY (OSA)

Executive Director Karsten Buse has been named a Fellow of the Optical Society (OSA).
The honorary title of Fellow of the Optical Society is awarded to members of the OSA for special contributions to the field of optics and photonics. Physicist Karsten Buse has been honored with the title "for fundamental work on the optical properties and applications of lithium niobate." The Optical Society (formerly Optical Society of America) was founded in 1916 with the aim of increasing knowledge and understanding in the fields of optics and photonics. It is recognized as the most important association within the optics community worldwide.

> Dr Christoph Werner (2nd f.l.) accepts the Hugo Geiger Prize from Hubert Aiwanger, Deputy Minister-President of Bavaria (l.) and Andreas Meuer (r.), board member of the Fraunhofer-Gesellschaft.

DOCTORATES AT FRAUNHOFER IPM

Fraunhofer IPM supports PhD students with its own doctoral program.
In 2018, twelve PhD students carried out research toward their doctorates at our institute. A further 15 doctoral students were supervised by institute staff members working with three professors at the University of Freiburg. The young academics work on highly application-oriented research questions. At the same time, independent scientific research that meets high scientific standards is required. The doctoral program, started in 2014, supports them in doing so. They are able to present and discuss the current status of their thesis. The program also allows them to gain insights into various research topics and acquire methodological skills from experienced members of staff. Aside from tutorials on scientific work, the students also learn about topics such as presentation techniques and publishing articles in specialized publications.

TALENTA

In 2018, four female staff members from Fraunhofer IPM took part in the Fraunhofer-Gesellschaft's TALENTA career program.
PhD students Laura Engel, Lena Maria Maier and Annelie Schiller were supported as part of TALENTA start.
Dr Katharina Predehl, project manager in the department for object and shape detection, is taking part in TALENTA speed up. The program supports female scientists aiming to assume responsibility in leading or specialist positions. The Fraunhofer-Gesellschaft has been promoting female scientists and management staff within the framework of the TALENTA career program since 2013. The program aims to provide personalized support to exceptionally talented staff members at all stages of their professional development, whilst also attracting new female scientists to Fraunhofer.

"Talenta gives me more freedom to expand on specific aspects of my research topic", says Annelie Schiller, who is writing her doctoral thesis at the institute on the subject of digital holography.

HUGO-GEIGER-PRIZE 2019

Dr Christoph Werner receives junior research award for developing novel laser light source.
As part of his doctoral work at the University of Freiburg's Department of Microsystems Engineering IMTEK, and in collaboration with Fraunhofer IPM, microsystems engineer Christoph Werner developed an extremely compact laser source with tunable output wavelengths. The laser source is based on a whispering gallery resonator and uses optical feedback to stabilize the light waves inside the resonator. To create the resonator, he stepped into unknown territory and, instead of a disk, used a ring mounted on a piezoelectric actuator. When voltage is applied, the actuator expands, and with it the ring. Tuning the resonator geometrically instead of thermally, as is usually the case, brings some key advantages. Namely, tuning is accelerated by a factor of 100,000 and at the same time becomes more independent of the wavelengths.

Through his work, Werner has laid the foundations for a new generation of laser light sources, which may become so small and cost-effective that they could one day be integrated into smartphones. This opens up applications for a wide range of users which, to date, required specialized lab-based lasers. A new crystal structuring technique was also created as a "by-product" of the thesis. Fraunhofer IPM has since been conducting license negotiations with one of the international market leaders in this field.

"TRACK & TRACE FINGERPRINT" WINS INNOVATION CHALLENGE

Fraunhofer IPM is able to beat off international competition as one of two winners in the Swedish SmartSteel Innovation Challenge.
The competition sought processes that enable marker-free tracing of steel products. In late 2018, 26 teams from all over the world had applied themselves to finding a solution. Fraunhofer IPM impressed the jury with its "Track & Trace FINGERPRINT" marker-free tracing method. Swedish special steel manufacturers Sandvik Materials Technology and SSAB launched the SmartSteel Innovation Challenge in the fall of 2018. The aim was to improve methods for reliable steel product tracing – by developing a sort of fingerprint – using open innovation methods. Of the 26 entries submitted from across the globe, seven teams were selected by the organizers and invited to the final in Stockholm.
A representative from each of the teams presented the different solutions to the expert jury. The judges then finally voted for the concepts presented by Fraunhofer IPM and Sweden's Luleå University of Technology. "We are particularly delighted that we will now be able to continue developing the 'Track & Trace FINGERPRINT' technology together with SSAB and Sandvik," says Dr Tobias Schmid-Schirling, manager of the Inline Vision Systems group. "This is the next step in bringing the technology to market on an even larger scale.«

Dr Tobias Schmid-Schirling (right) accepted the award in December 2018 in Stockholm.

< Topping-out ceremony on Georges-Köhler-Allee 301: Construction workers and managers as well as several representatives of the institute celebrated completion of the shell construction in March 2018.

NEW BUILDING STILL ON SCHEDULE AND WITHIN BUDGET

Up to one hundred skilled personnel at a time have been working on the new institute building.

Work on the new building continued at full steam in 2018. A topping-out ceremony was held on March 26 to celebrate completion of the shell. The addition of windows and doors in the fall made the building dry and watertight, meaning that work could begin on the interior finishing, building services, and insulation. This work, as well as the mounting of the exterior façade, will continue throughout 2019. Many staff members took the opportunity for a lunchtime tour of the site with the Head of Technical Services, Clemens Faller. If everything continues on schedule, activities will relocate to the new building in early 2020.

A LIFE DEDICATED TO SPACE RESEARCH

The founder of the Fraunhofer Institute for Physical Space Research, Professor Karl Rawer, passed away two days before his 105th birthday on April 17, 2018 in March, Germany.

The present-day Fraunhofer IPM emerged from this institute, which was founded in 1973 and managed by Rawer up until his retirement in 1979. Born in Neunkirchen, Germany, Rawer is considered one of the early pioneers of European space research. His life's work concerned researching the ionosphere, which is the part of the Earth's upper atmosphere in which short waves are reflected. These are important for worldwide radio communication. Rawer played a significant role in establishing the standard ionosphere model "International Reference Ionosphere" (IRI), which has been valid internationally since 1999. The physicist first gained standing among his peers with works on the propagation and geophysical influencing of radio waves. Rawer moved into satellite research after the end of the war. He was an honorary doctor of Heinrich Heine University Düsseldorf, a corresponding member of the Austrian Academy of Sciences and the International Academy of Astronautics, and a recipient of the Cross of Merit of the Federal Republic of Germany, 1st class. International scientific collaboration and dialogue was always especially important to him. Rawer lectured at Sorbonne University in Paris for many years. His scientific work, his personality and his warm manner have been part of the institute's DNA from the very beginning. Professor Rawer remained connected to the institute into old age and followed its development with great interest and a sharp mind.

Karl Maria Alois Rawer remained connected to the institute until the very end of his life.

> Exploring quantum physics: QUILT Autumn School participants in front of the German Physical Society's Physikzentrum building in Bad Honnef.

"THINKING CLUB" – CREATIVE, NOT ELITIST

Where, precisely, do ideas hide before we find them? Many often emerge from the "Thinking Club", a new monthly discussion group at Fraunhofer IPM.

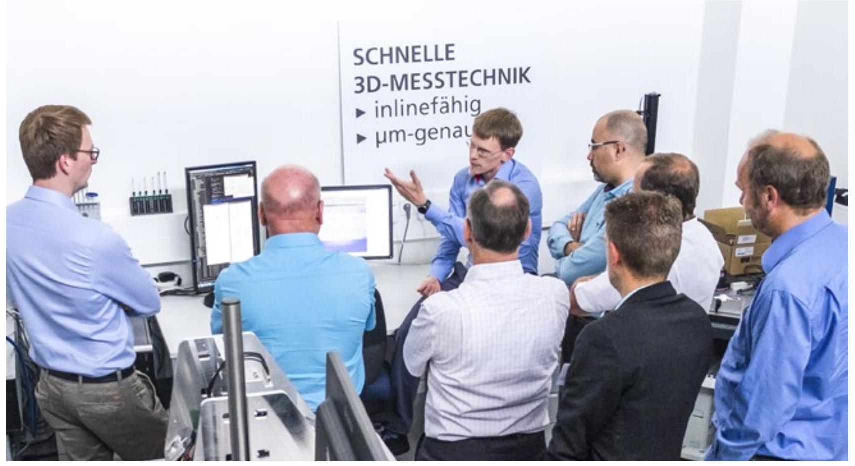
In theory, the path to innovation is extremely straightforward. You become aware of something interesting, think it over, maybe you connect it to something you already know, and then you just have to develop a little something, solve a few minor issues and voilà, innovation achieved – in theory… In practice, however, things are often very different. What innovations would actually be of interest – to our clients and to Fraunhofer IPM? What new directions should we pursue, what new expertise should we focus on developing? In 2018, Fraunhofer IPM established a new format for discussions to seek answers to typical questions such as these. Every person who works at the institute can suggest topics to be discussed with around a dozen colleagues at the Thinking Club – there is no set formula, leaving room to welcome unusual perspectives. This allows us to find new fields of application for expertise we already have, and to develop new skills relating to familiar fields of application in a targeted way – success is by no means guaranteed, but it is increasing.

INDUSTRY WORKSHOP ON "OPTICAL GEAR MEASUREMENT"

Around 40 measurement technology specialists and users met in mid-June 2018 for the first industry workshop on optical gear measurement.

The event at Fraunhofer IPM was organized by a team led by Annelie Schiller and Dr Alexander Bertz in coordination with Alicona Imaging GmbH. Manufacturers and users in the gear technology sector, as well as measurement technology specialists, learned all about the latest technological developments in optical gear measurement at eight specialist lectures. During a lab tour and exhibition, Fraunhofer IPM presented digital holographic measurement systems for measuring gears used in the automotive and aviation sectors, as well as a method for marker-free component tracing. Alicona Imaging presented an optical measurement system for small-scale precision gearing.

Optical gear measurement offers a number of advantages over conventional tactile measurement – optical methods are quick and precise and deliver measurement data on the entire tooth flank surface. As many modern production processes and applications in gear technology require the utmost precision, the 100 percent component control enabled by these new methods is increasingly in demand. Future industry workshops will take place every other year.



Dr Tobias Beckmann introduces workshop attendees to a digital holographic system for gear measurement.

QUILT AUTUMN SCHOOL

The focus of this conference in Bad Honnef, jointly organized by Fraunhofer IPM and Fraunhofer IOF, was quantum imaging.

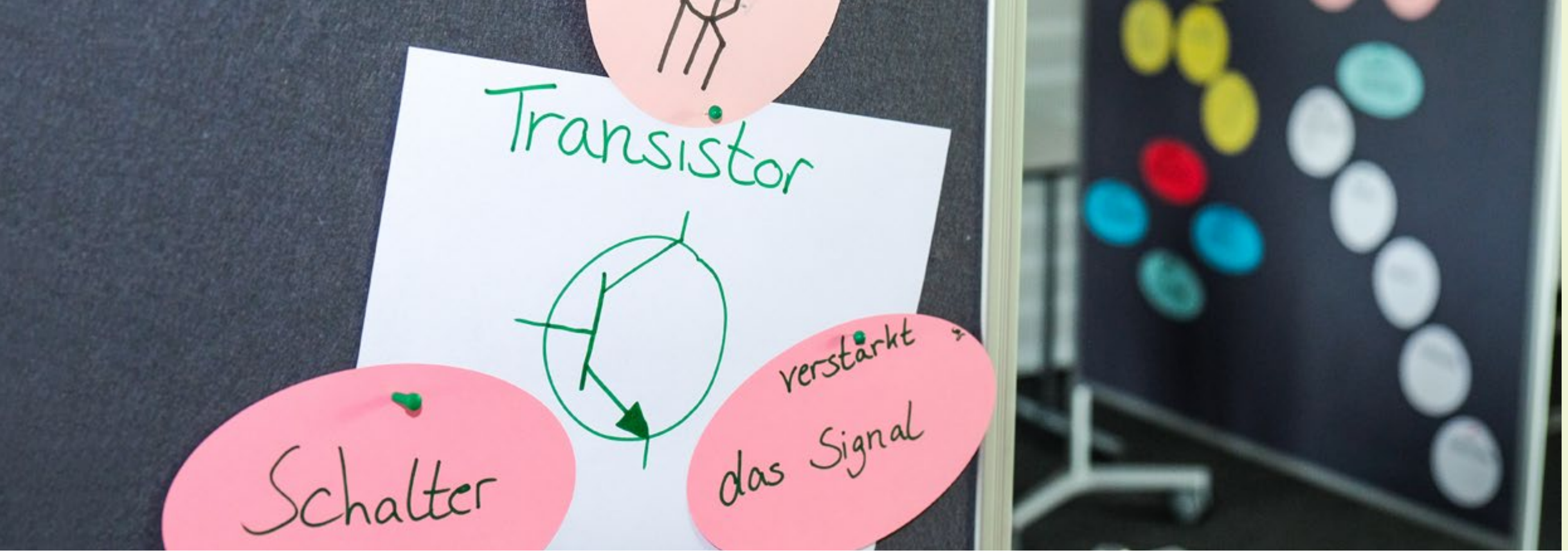
Over the course of the four-day Autumn School on the subject of Quantum-Enhanced Imaging and Spectroscopy in September 2018, scientists and industry representatives met for the first time to exchange ideas on the physical principles, technological aspects and possible applications of quantum imaging. The international conference was the first event on quantum-enhanced imaging to take place in Europe, and welcomed a host of distinguished attendees. The Fraunhofer-Gesellschaft is focusing on quantum imaging in its lighthouse project QUILT (Quantum Methods for Advanced Imaging Solutions). Aside from Fraunhofer IPM, five additional Fraunhofer institutes and two external research units are involved in the QUILT project. "The Fraunhofer-Gesellschaft can draw on an extremely wide range of outstanding know-how concerning optics and semiconductor technology," says Professor Karsten Buse, who is coordinating the project in tandem with Professor Andreas Tünnermann, Director of Fraunhofer IOF. "That is our basis for exploring and harnessing the most fascinating and simultaneously the most difficult spectra for imaging and analytics using quantum technology concepts."

MOLAS WORKSHOP BECOMES A REGULAR FIXTURE

Around 100 participants attended the third Mobile Laser Scanning Technology Workshop.

Experts from both research and industry provided insights into current technological developments in laser scanning, with a special focus on underwater laser scanning. The latest findings from this relatively young field of application were presented over four presentations. The program also covered the latest trends in scanner systems, calibration issues, and data interpretation and visualization. In his keynote speech "Laser scanning – a game-changing technology", Jürgen Mayer from Leica Geosystems demonstrated the numerous untapped applications for mobile laser scanning. These range from high-resolution digital 3D maps to autonomously created 3D maps and even to the creation of 5G network maps. Reason enough, then, to discuss the progress of these developments again at the fourth MoLaS Technology Workshop, which will take place on November 11 and 12, 2020 in the new institute building.

Advances in airborne laser scanning met with great interest, while underwater laser scanning was the focus of the MoLaS Technology Workshop 2018.



< Bucking the digital trend – school pupils used a flipchart to present what they learned during their internships.

SCHOOL MEETS RESEARCH

Young students experience some hands-on science at Fraunhofer IPM.
At the nationwide Girls' Day event, twelve eighth- and ninth-grade girls were given a tour of our laboratories and workshops. Some of the day's activities included light experiments, building a lie detector, microchip processing, learning about the operating principles of a computer, and practical skills such as soldering wires. Under the umbrella of two internship programs directed at high-school students, BOGY and TOP BORS, a group of around 18 boys and girls spent one week each in the institute's labs and workshops in 2018.

Promoting young talent: schoolgirls experiment with cleanroom techniques.

COMPETITION FOR THE BEST APPRENTICES

Attracting the brightest minds early on – Freiburg's five Fraunhofer institutes joined forces to recruit new apprentices.

In 2018, Fraunhofer IPM took part in two regional information and contact fairs on the subject of apprenticeships.
IPM staff members attended the Freiburg Job Start Börse career fair in May. With the motto "Apprenticeships at the intersection between science and industry," the various Freiburg Fraunhofer Institutes showcased themselves together as an attractive employer for vocational careers, too. And interested parties had the opportunity to speak not only with some of the Institutes' instructors, but also with some of their apprentices at the marktplatz: ARBEIT SÜDBADEN career fair in November.

Fraunhofer IPM provides training in three professions: Electronics engineer (specializing in devices and systems), computer engineer (specializing in systems integration) and industrial mechanic (specializing in precision and device technology). A total of six apprentices were employed by the institute in 2018.

Angelina Hotz completed her apprenticeship as a computer engineer in the field of systems integration with outstanding results. Angelina will continue to work for the IT and telecommunications technology department after graduation and was elected to the position of youth and trainee representative in November 2018.

THREE QUESTIONS TO... NICOLAS REINEBECK

Nicolas Reinebeck is a chemist and patent examiner, and has been responsible for intellectual property rights at Fraunhofer IPM since mid-2018. He not only oversees the institute's patent strategy, but above all supports colleagues in the specialist departments with everything from research through developing and formulating patent claims to applying for intellectual property rights. This allows us to offer our customers innovations, while at the same time ensuring that they have plenty of room for manoeuvre.

"An exciting invention transcends conventional approaches and received wisdom," says Nikolas Reinebeck, who has been responsible for property rights at the Institute since 2018. A solid patent strategy ensures our customers have room for maneuver.

Mr. Reinebeck, how can you really tell if something truly is a good invention?
I wouldn't want to use the words good invention, because that would mean there had to be a bad invention as well. And that wouldn't be fair on the inventor. I prefer to talk about exciting inventions. For me, an exciting invention is one that re-imagines familiar solutions, disregards the limits imposed on thinking, and thus arrives at new solutions. There are no restrictions on thinking at Fraunhofer IPM; we are open to everything and this is how we create the right conditions for truly exciting patents.

How do you support your colleagues in their research work?
It begins right at the initial stage of idea generation. You can achieve a lot with focused research if you know what others have already considered. This can therefore be used as a basis to decide which direction to take. I typically experience a lot of surprise from colleagues when they see the other solutions that have been tried in the past. This knowledge allows us to better differentiate ourselves and to say, okay, something has already been done here. So we go in a different direction, but consequently we make the most of this prior knowledge and allow ourselves to be inspired by it. At the same time, we also gain insights into the market and the market players.

What is the added value that our clients gain from your expertise?
Generally speaking, good research leads to a better patent application with a wide range of protection. Our clients then benefit from this broad scope of protection. This is because more extensive patent protection leaves very little room, or ideally no room at all, for others to circumvent it – and this is precisely what our clients want.

> Dr Jochen Kopitzke: "Magnetocalorics offers a great deal of potential for disruptive innovation and could replace compressor refrigeration technology in the intermediate term."

>> In 2017, Philipp Kirsch GmbH moved from Offenburg to the neighboring town of Willstätt. The company's new building includes 4,500 square meters of production space and 2,000 square meters of storage space.

"Projects like these are fun, and it's important to have fun!"

Dr Jochen Kopitzke studied Economics in Tübingen and completed his doctorate in Mannheim, Germany. He has been owner and Managing Director of Philipp Kirsch GmbH since 2010. Now forty years old, he already knew as a student that he wanted to take on a management role in a mid-sized company. Together with Fraunhofer IPM and other partners, Philipp Kirsch GmbH is developing a market-ready magnetocaloric refrigerator.

Mr. Kopitzke, what are Philipp Kirsch GmbH's main products?

We manufacture medical refrigerators and freezers which offer advanced precision for storing valuable goods. We are Germany's market leader in this area. You can find our products across Germany in nearly all hospitals, in many laboratories associated with the pharmaceutical industry, and in pharmacies.

Is there a global trend being observed in medical refrigerating technology?

More importance is being placed on healthcare worldwide. Even newly industrialized countries are continuously improving their healthcare systems. We already supply our products in over 100 different countries. The high-quality storage of medication is thus becoming more and more important – and quality assurance is key. Some doctors used to use domestic refrigerators to store vaccines. Quality standards are higher now, due to regulatory requirements. Electronic quality documentation pertaining to storage conditions is also becoming more and more important.

What led to the first project with Fraunhofer IPM?

At the beginning of 2012, we at Kirsch started to concentrate more closely on magnetocalorics. At that time, we were already working on a preliminary study with the University of Freiburg. We then started implementing this technology with a project partner from Alsace. With this partner, we developed the first magnetocaloric refrigerator – working towards a cold side temperature of 5 degrees – and presented it at Medica 2015 in Düsseldorf. However, it soon became clear that the technology of active magnetocaloric refrigeration that we'd used had reached its limits, and so we entered into talks with experts from Fraunhofer IPM and brainstormed the possibility of a joint project. The impetus to make contact came from the State Ministry for Economic Affairs in Baden-Württemberg, since Fraunhofer IPM had made great advances in magnetocalorics based on its patented system concept as a part of a project backed by the state.

Did you already have a target product in mind at the beginning of your collaboration?

Yes – precisely the product that we are currently working on together; we want to use magnetocalorics to introduce a device to the market that's capable of reaching -86° C. Our customers are already requesting such a product. And it was clear to me that I wouldn't be able to achieve anything with compressor technology – there are already enough manufacturers working in that area. Instead, I wanted to take the next step and create an innovative product based on an extremely reliable and energy-efficient technology, which meant restarting with a completely new approach. Magnetocalorics offers a great deal of potential for disruptive innovation and could replace compressor refrigeration technology in the intermediate term. We have found a clear market that we would like to tap into.

What do you see as crucial for successful collaboration?

I believe it is important to work on projects that one finds interesting, to be open to new things and to have the right partner on board – with a project duration of three years, it's important to have a streamlined, effective team. In terms of project management, it's good to set regular appointments and deadlines and be sure to keep track of them. Last but not least, the chemistry has to be just right. It can make things very difficult if someone is not prepared to share created knowledge with the rest of the project team. The collaboration within our project team is excellent – we're forthright, purposeful and productive. We aren't scattered thousands of kilometers away from each other. We are extremely supportive of one another. Nobody says, "That's not my job; that's your job!" We are united by a common purpose.

What do you appreciate about working together with Fraunhofer IPM?

First and foremost their experience and knowledge in the area of magnetocalorics, of course. Fraunhofer IPM holds an important patent, the employees are highly skilled, and so many technical resources are available for properly investigating relevant topics. Working at the institute is wonderful in terms of the technology, the expertise, and the people, and it's really a level playing field. Projects like these are fun, and it's important to have fun!

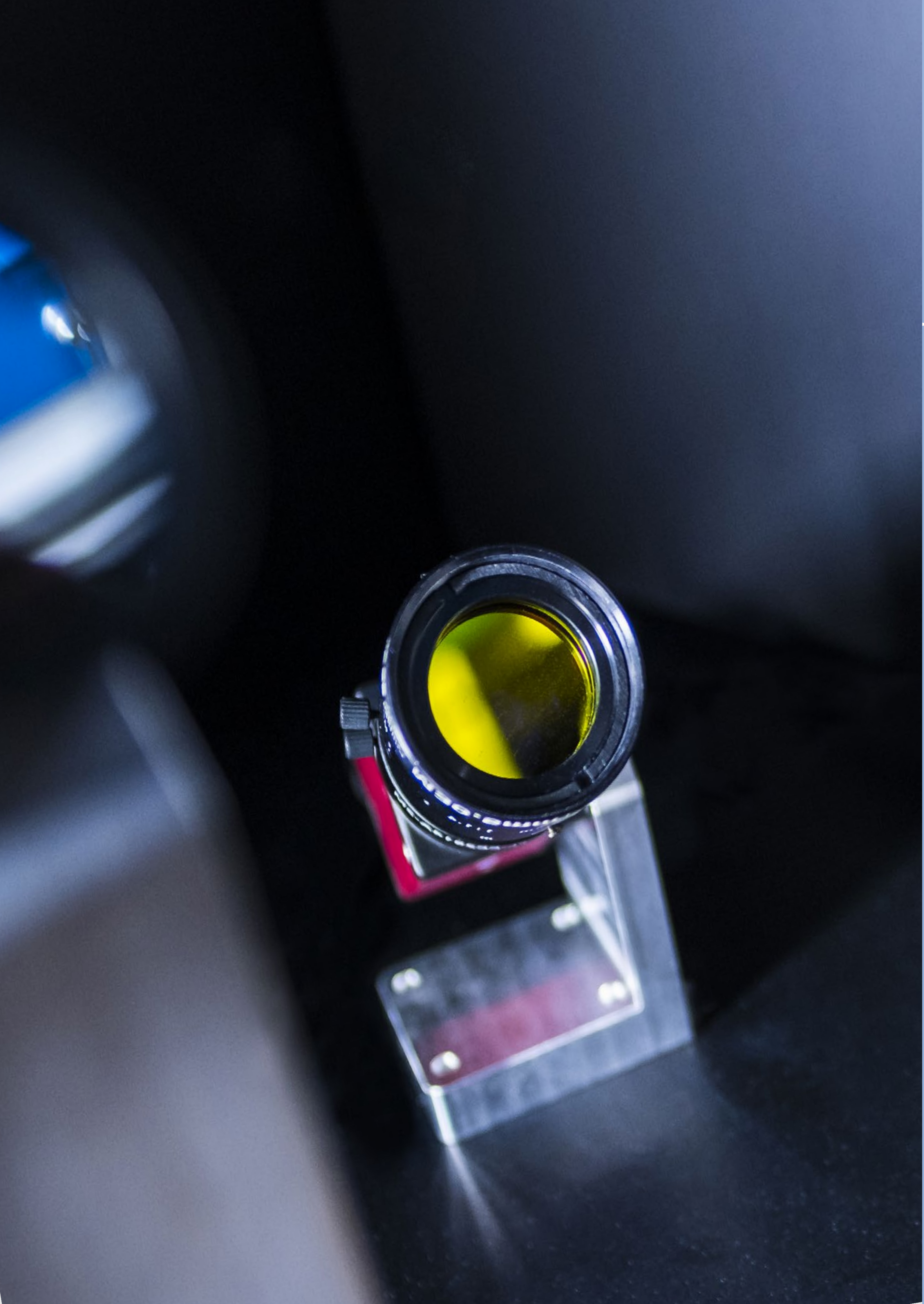
What do you develop yourselves and what is accomplished with external partners?

We have over 60 years of experience in calibrating individual components within refrigeration technology products. We do all of that ourselves. Otherwise, we only develop things in house if we have all the necessary skills. Everything else is done in collaboration with partners we can trust.

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

Philipp Kirsch GmbH located in Willstätt, Baden-Württemberg, Germany, is a globally active manufacturer of professional refrigerators and freezers for the healthcare industry and laboratories and is the market leader in German hospitals. Its broader customer base includes pharmacies, blood banks and chemical and pharmaceutical companies. It was founded in 1865. Together with Fraunhofer IPM, Philipp Kirsch GmbH is developing an innovative refrigeration technology based on magnetocaloric materials for particularly efficient and environmentally friendly cooling. For more information, visit www.kirsch-medical.de

A cooling cycle can be realized using magnetocaloric materials. Fraunhofer IPM holds an important patent for a particularly fast cooling cycle.



"Our measuring systems help you optimize manufacturing processes."

For production control, Fraunhofer IPM develops optical systems and imaging methods. The systems can be used to inspect surfaces and measure complex 3D structures during production and thus to control processes. The systems measure fast and accurately so that small defects or impurities can be detected and classified in real time, even at high production speeds. Combined with (mark-free) individual component tracking, 100 percent real-time control and direct feedback into production is possible 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. The systems, optimized to meet customer specifications, are used in applications such as forming technology in the automotive industry and for quality assurance in medical products through to electronics production.

Group **Optical Surface Analytics**

- Purity control and coating inspection
- Inline microscopy
- Laser-induced breakdown spectroscopy

Group **Inline Vision Systems**

- Surface inspection shape measurements
- Inspection of strip materials
- Marker-free component identification

Group **Geometrical Inline Measurement Systems**

- Inline component testing
- Gearwheel measurement
- Dynamic deformation measurement

< One of multiple cameras in the F-360° inspection system, which detects contamination on component surfaces in free fall with no need for time-consuming handling.

CONTACT

Dr Daniel Carl
Head of Department
P +49 761 8857-549
daniel.carl@ipm.fraunhofer.de

BUSINESS UNIT **PRODUCTION CONTROL**

GROUP **OPTICAL SURFACE ANALYTICS**

Dr Albrecht Brandenburg, P +49 761 8857 - 306, albrecht.brandenburg@ipm.fraunhofer.de

The main focus of this group is the development of turnkey devices for surface analysis. These devices use fluorescence measurement techniques as well as infrared reflection spectroscopy and laser-induced breakdown spectroscopy. Fraunhofer IPM's long-standing experience in systems engineering encompasses optical units, image recording and image processing.

Group Manager: Dr Albrecht Brandenburg

>> Even single particulate impurities on components can be detected and classified by combining different imaging techniques.

EXPERTISE

Fast, spatially resolved fluorescence measurement techniques with customer-specific lighting systems | Laser-induced breakdown spectroscopy | Inline microscopy systems with control units and data evaluation | Short-wave-infrared analysis: harnessing spectral dependence of absorption and scattering properties for materials analysis | Analysis of biochemical reactions with the help of fluorescence markers

APPLICATIONS

Inline purity control, revealing impurities on component surfaces | Detection of surface defects and surface coatings | Comprehensive oil film measurement of strip ware or complex 3D free-form components during production | Authenticity check by analyzing fluorescent pigments | Microscopy at production speed, e.g. 100 percent quality control of key components in medical devices | Substance-specific identification of materials on surfaces | In-vitro diagnostic systems

SPECIFICATIONS

PURITY CONTROL AND COATING INSPECTION

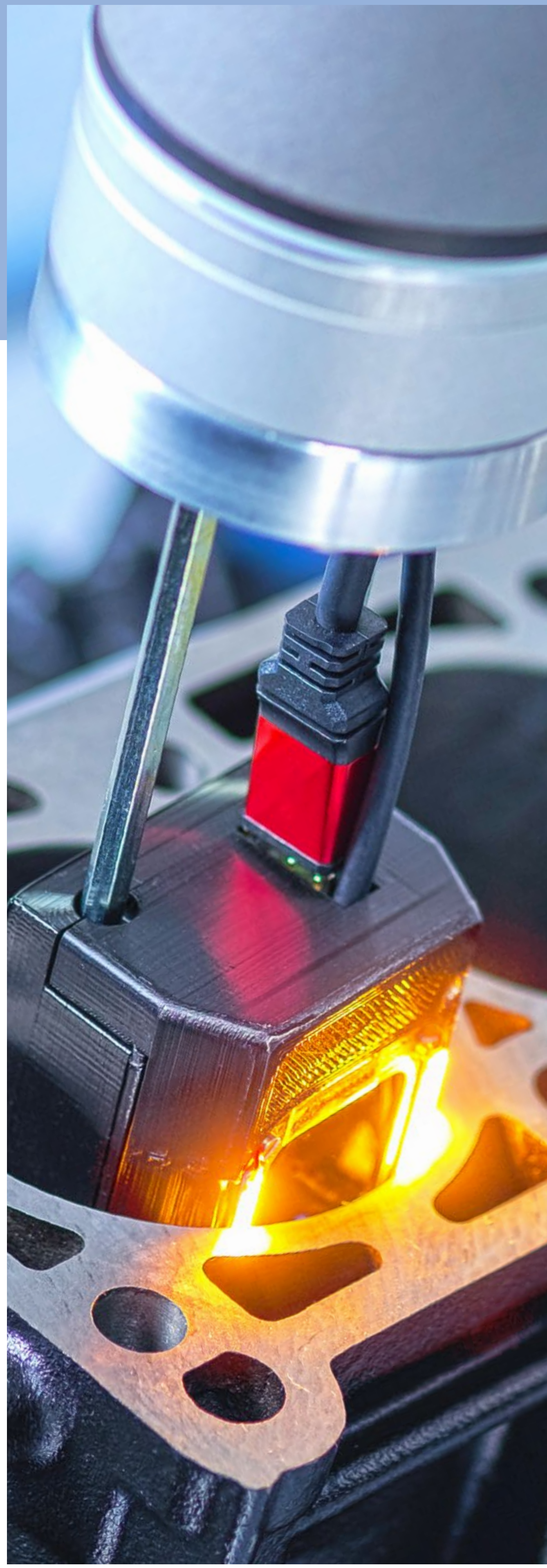
- Detecting position, form and quantity of film-like impurities at production speed
- Imaging detection of process auxiliaries such as lubricants, greases or cleaning agents (detection limit for standard lubricants: 0.01 g/m²)
- Camera system: detection area of some cm², optical resolution approx. 20 µm
- Scanner system: detection area of some m², optical resolution approx. 500 µm

INLINE MICROSCOPY

- Characterization of complex 3D microstructures
- Detecting structural defects, impurities, defective geometries or scratches
- Reproducibility of distance measurement in the sub-micron range
- Measuring device capability for determination of component geometries
- Frequencies of approx. 1 second

LASER-INDUCED BREAKDOWN SPECTROSCOPY

- Non-contact materials analysis on surfaces
- Layer thickness measurement of functional surfaces with thicknesses in the micrometer range
- Inline characterization of nanometer-thin anticorrosive coatings
- Detection of element concentrations in coatings in the order of ppm



< Functional coatings, which are sometimes just a few nanometers thick, must be homogeneous and complete. ANALIZEsingle measures the layer thickness, elemental composition and elemental distribution during the coating process.

GROUP **OPTICAL SURFACE ANALYTICS**

Inline checks on thin coatings

Functional coatings are often applied to industrially manufactured components to protect against corrosion, to give them special finishes or as surfacers. These coatings need to fulfill stringent quality specifications if the components are later to be used in high-tech products. The ANALIZEsingle optical measurement system is the first of its kind to monitor the integrity, layer thickness, and elemental distribution of coatings during production.

LASER-INDUCED BREAKDOWN SPECTROSCOPY (LIBS): A short-pulse laser ablates just a few cubic micrometers of material from a surface. This material forms a mixture of charged particles, called a plasma, which emits a material-specific light spectrum, similar to a spark. Spectral analysis of the emitted radiation enables the elemental distribution of the ablated material to be determined. The tiny amount of material removed is not critical for the vast majority of applications. In exceptional cases, for example when coating extremely smooth surfaces, measurements can be performed in less significant areas such as on cutting edges.

Anyone who has ever painted a window frame will understand the difficulty involved in covering surfaces with a flawless coating. This becomes infinitely more difficult when applying coatings as thin as just a few nanometers onto components with highly complex shapes. A variety of techniques are employed to do this, such as sputtering, electroplating, and precipitation reactions using spray or immersion coating processes. Faults in the coating process are not simply an aesthetic problem, however. Coatings that are incomplete or not homogeneous may subsequently impair the functionality and quality of the entire end product. If we consider faulty coatings intended to protect against corrosion, or incomplete coatings of surfacers intended to ensure durable adhesion of paint onto car bodies, the logic of this becomes immediately clear. Yet it also holds true for coated electronic components, where wafer-thin layers of copper are employed for thermal conduction or contacting, since substandard coatings here may cause the components to fail.

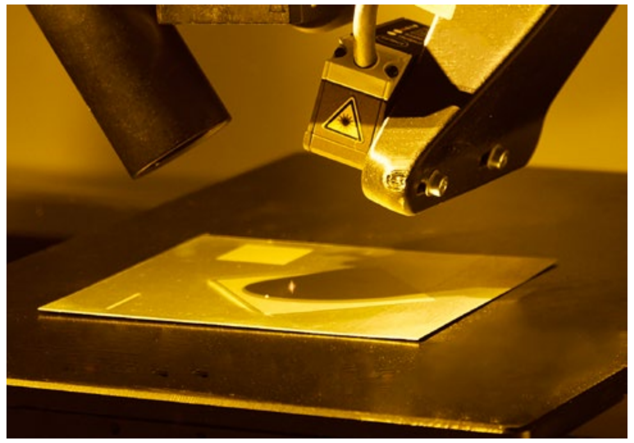
As it is not always possible to reliably achieve a homogeneous application of coatings, the ability to continuously measure layer thickness is extremely beneficial for process monitoring and quality assurance. Popular techniques for determining elemental composition, such as X-ray fluorescence (XRF), energy-dispersive X-ray spectroscopy (EDS), glow discharge optical emission spectroscopy (GDOES), secondary ion mass spectrometry (SIMS), and X-ray photoelectron spectroscopy (XPS), are not suitable for use during the production process and also have limitations in terms of the elements which they can detect. Only X-ray fluorescence is suited to use on production lines. However, extremely thin layers, such as corrosion protection coatings measuring just a few nanometers, cannot be detected on the production line.

Material plasma gives insights into elemental composition and distribution as well as layer thickness

The ANALIZEsingle coating thickness measurement system has made it possible, for the first time, to perform spatially resolved measurements of chemical element distribution on component surfaces during production. This elemental analysis allows the thickness of nanometer-range coatings to be determined with an accuracy of ±10 percent. In order to determine the coating thickness at a given measurement point, a special form of laser-induced breakdown spectroscopy is used. All that this requires is a single laser pulse, which ablates material from both the coating and the component surface. The emission spectrum characteristics of the coating and component materials are then compared with one another, making it possible to calculate the coating thickness. At the same time, the spectrum provides information on the mixing ratio of the coating components, which allows checks to be performed on the homogeneity of the coating compositions. The spectrum is analyzed immediately after the measurement is performed, allowing the coating process parameters to be not only monitored, but also quickly readjusted if necessary.

Layer thickness determined in under a second

The ANALIZEsingle is positioned within the production line such that the sheet metal is fed around a deflection roller at the measurement spot. To enable more extensive measurement across flat surfaces, the intention is to further develop the measurement head so that it can be moved over the entire width of the production line. In the inline system, the number of measurement points per surface area is given by the repetition rate of the laser, of up to 100 pulses per second, and the feed rate of the conveyor, in the order of magnitude of a few meters per second. For example, 50 measurement points per meter are possible with a speed of two meters per second. Since small-scale differences in coating thickness are not always important, it is possible to perform averaging across several measurement points. Even when this is done, the coating thickness is still determined in under a second. Measurement data are automatically saved and can be used as control parameters as well as to enable cross-process optimizations for the purposes of data collection in line with Industry 4.0 specifications.



Controlled material ablation via laser pulse is a prerequisite for high repeatability. Short-pulse lasers with high levels of pulse-to-pulse stability are employed.

Dr Albrecht Brandenburg, P +49 761 8857 - 306, albrecht.brandenburg@ipm.fraunhofer.de

GROUP **INLINE VISION SYSTEMS**

Dr Tobias Schmid-Schirling, P +49 761 8857-281, tobias.schmid-schirling@ipm.fraunhofer.de

The group's research focus is on highly accurate customized inspection systems which inspect component surfaces down to the micrometer during production. The camera-based systems inspect the components for compliance with quality criteria using fast, low-level image processing driven by state-of-the-art algorithms – over the entirety of the component surface if necessary. At the same time, a digital fingerprint can be generated for each individual component by means of the component's surface microstructure, to be used for tracking. This marker-free Track & Trace system is combined with individual inspection data to pave the way for the comprehensive digitalization of production processes in line with Industry 4.0.

Group Manager: Dr Tobias Schmid-Schirling

>> Inline inspection of sheeting requires extremely short exposure times to generate high-resolution images of the measurement object as it moves.

EXPERTISE

Fast, image-based inspection of surfaces | Multi-camera systems for complete inspection of components | Algorithms for analyzing microscopically small surface structures

APPLICATIONS

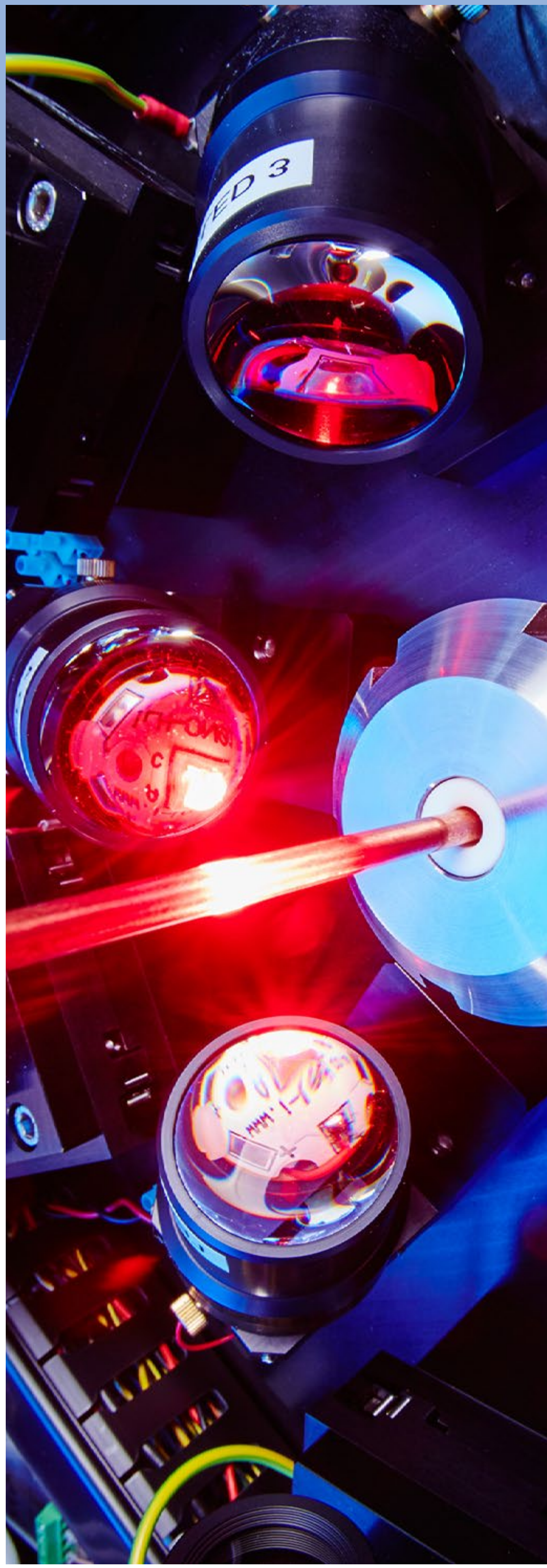
Inspection systems for quality control of sheeting and long products | Customized inspection systems for complete inspection of components with a complex shape in second intervals (Inspect 360°) | Reading systems for secure, marker-free identification of individual components at the rate of production (Track & Trace FINGERPRINT)

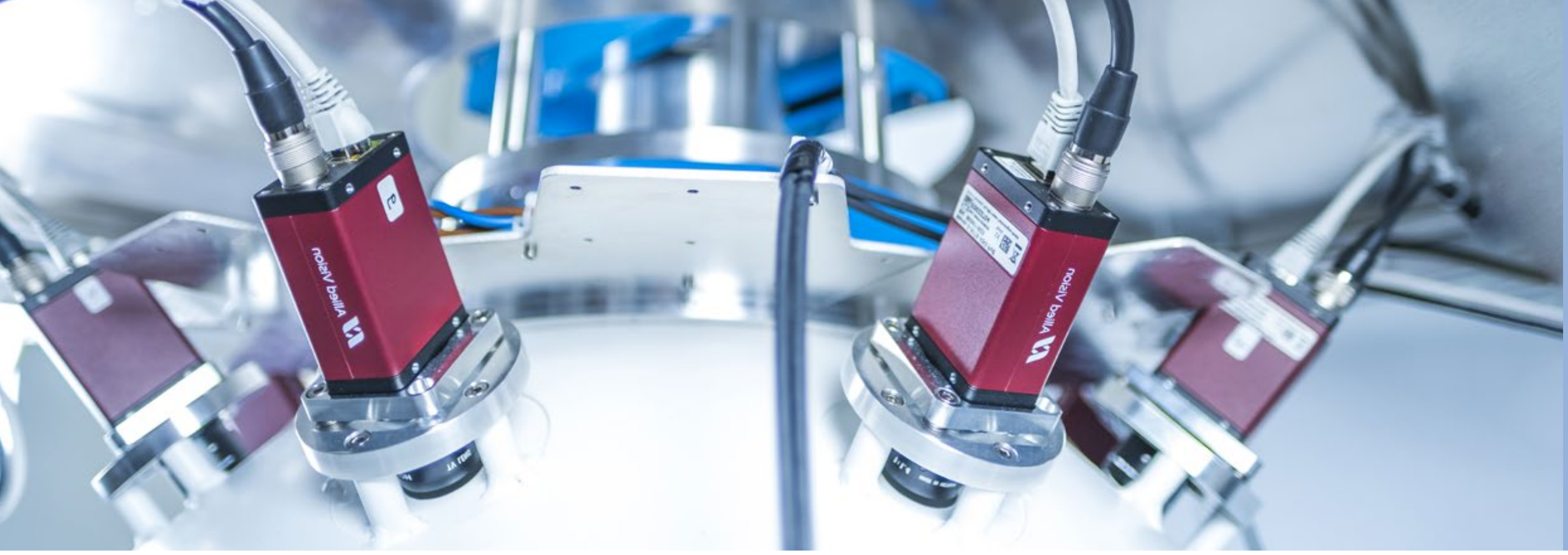
SPECIFICATIONS

100 PERCENT, CONTINUOUS MONITORING
- Surface monitoring of wires, cables and bands as well as pipes, rods and profiles
- In real time up to 30 m/s
- Inline defect detection down to 50 µm
- Automatic detection, classification and documentation of defects

INSPECT 360°: COMPONENT INSPECTION IN FREE FALL
- Full inspection of the component surface for geometric defects and surface defects
- Inline inspection of different components with no need for specific handling or adjustment
- Defects > 100 µm detectable in one-second intervals

LASER-INDUCED BREAKDOWN SPECTROSCOPY
- Reliable image-based tracing of mass-produced parts in batches of many millions
- Can withstand local surface damage and impurities
- Small signature IDs (of only a few kB) enable rapid recognition at the rate of production





< To date, quality testing on mass-produced parts has been thwarted primarily by the need for component handling. Optical testing in free fall circumvents this problem.

GROUP **INLINE VISION SYSTEMS**

No need for handling: Component inspection in free fall

Large quantities, low prices – and high quality standards: Quality control on mass-produced parts presents many manufacturers of semi-finished products with problems that are almost impossible to solve. For automated optical inspection procedures, components must be oriented and positioned in a specific way. But it is disproportionately expensive to handle bulk goods in this manner. Inspect 360° from Fraunhofer IPM provides the answer. This optical system analyzes the geometry and surface condition of components in free fall – with no need for special handling.

Most products consist of a large number of individual components. In a single car alone, there can be up to a thousand different semi-finished metal or plastic items. These cast, blanked, drawn, and forged parts are produced at one-second intervals and transported on as bulk goods. Despite their low cost, they later perform important tasks in the finished product. Once they are installed, geometric deviations, defective surfaces, and contamination can have fatal consequences, for example where chassis and brake components, prosthetics, or drug dosing devices are concerned. As a result, strict statutory quality standards apply, particularly in industries where safety is an issue, such as the automotive, aviation, and medical technology sectors. It is therefore all the more astonishing that manual visual inspections and tactile gauging checks are still often the best methods available today for inspecting the quality of mass-produced parts.

Handling-free inspection

Optical measurement technology is capable of inspecting the dimensional accuracy and any surface defects of components with great reliability and precision. The problem with bulk goods, however, is the component handling that this requires. Parts tumble out of blanking and casting machines at one-second intervals. Even modern robotics cannot keep pace with this, and would anyway be disproportionately expensive.

The Inspect 360° system jointly developed by Fraunhofer IPM and the Fraunhofer Institute for Computer Graphics Research IGD elegantly sidesteps the problem of handling. Components are carried in succession directly from the conveyor belt to a hollow sphere where they undergo optical analysis in free fall. Each component passes through the inspection sphere, which is designed like an integrating sphere with a diffuse reflective interior, in just a fraction of a second. Several things happen during this time. 27 cameras fully map the homogeneously lit surface of the falling object in a single shot. Individual areas of the object are photographed from different angles, which significantly improves the robustness of the technique. Alongside 24 high-resolution inspection cameras, three lower-resolution tracking cameras with wide-angle lenses map the position of the component, which can fall into the free-fall inspection system in any orientation.

F-360°: CLEANLINESS TESTING IN FREE FALL The sister system detects filmic contamination and particles on surfaces using fluorescence measurements. In order to perform these, the interior of the test space is illuminated by UV LEDs. This light activates the fluorescence of production residues such as oils, fats, and wet chemical cleaners. Any fluorescent light emanating from the surface is captured by six cameras. This results in an image showing all contamination across the entire object surface.

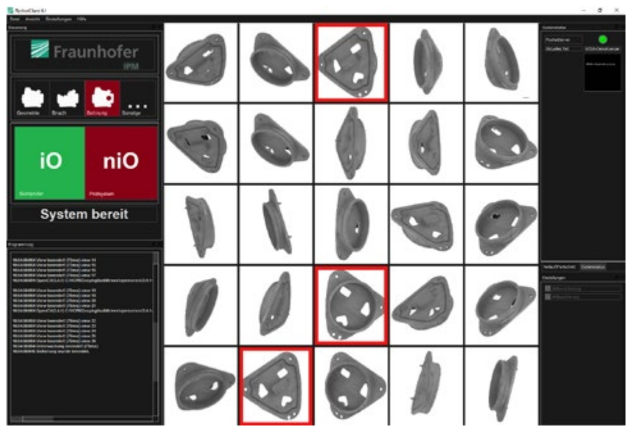
Real-time alignment with idealized 3D model

With this system, it is the geometry and surface condition of components that undergo analysis. The F-360° sister system additionally detects contamination and foreign particles. Any deviations in dimensional accuracy are determined by performing an alignment with a previously created, CAD-compliant 3D model of the component. Typical surface defects, such as cracks, holes, scratches, and spots, are detected by comparing the components with perfect parts. Geometric deviations, as well as cracks and pin-holes measuring just a few 100 µm, are detected in this process.

With the exception of optically inaccessible cavities and transparent components, the geometric complexity of components is of no consequence to Inspect 360°. The system can inspect components with diameters and edge lengths ranging from just a few millimeters up to diameters of 20 cm – test spaces are set up according to the specific requirements. Specially positioned, high-power LEDs ensure adequate lighting inside the hollow sphere. Apart from the two small openings for entry and exit of the components, the inspection system is fully encapsulated to ensure that any background or ambient light is completely blocked out.

"Bits not robots"

Inspecting components in free fall at the rate of production demands a great deal not only of the optics and system design, but also of the data processing technology. Specially developed AI-based algorithms determine the component type and the orientation of each test specimen directly after recording. The individual images are then matched to the corresponding view of the CAD model. In this way, the texture of the entire surface can be analyzed by real-time image processing. Defined areas of the model can be masked or examined for defects in more detail if desired. It is even possible to differentiate by quality class on the basis of previously defined deviations from normal. Quality-compliant parts are classified as such as they exit the test sphere, while faulty specimens are rejected.



Inspect 360° user interface: Image perspectives where defects have been detected are marked. By comparing the results of the visual inspection and the inspection system, inspection criteria and threshold values can be subsequently adjusted.

Dr Tobias Schmid-Schirling, P +49 761 8857 - 281, tobias.schmid-schirling@ipm.fraunhofer.de

GROUP **GEOMETRICAL INLINE MEASUREMENT SYSTEMS**

Dr Alexander Bertz, P +49 761 8857-362, alexander.bertz@ipm.fraunhofer.de

The group's research focuses on developing measurement systems that perform contactless, high-precision, inline measurements on the geometry and 3D surface structure of complex components, providing measurement data in real time. To do this, ultra modern optical measurement techniques, such as digital holography and speckle correlation, are combined with exceptionally fast evaluation procedures. This creates systems that, for the first time, are allowing gear geometries to be optically scanned in just a few seconds, workpieces to be measured directly in machine tools with the utmost precision, and the smallest stress-induced component deformations and cracks to be identified.

Group Manager: Dr Alexander Bertz

>> HoloGear, an optical gear-wheel measurement system based on multiwavelength digital holography, allows full measurement of all functional surfaces on a gear with micrometer precision.

EXPERTISE

Topography measurements using digital holography | Sub-µm scale planar measurement of geometric deviation in gears | Dynamic deformation and strain measurements on components and material compounds on the µm-nm scale

APPLICATIONS

Component testing in the machine tool to enable manufacturing and measurement with micrometer precision – workpiece can remain set up | Holographic systems for accurate, contactless, inline measurement of gear geometries | Non-contact, optical, strain-controlled cyclic fatigue testing to enable failure analysis

SPECIFICATIONS

INLINE COMPONENT TESTING

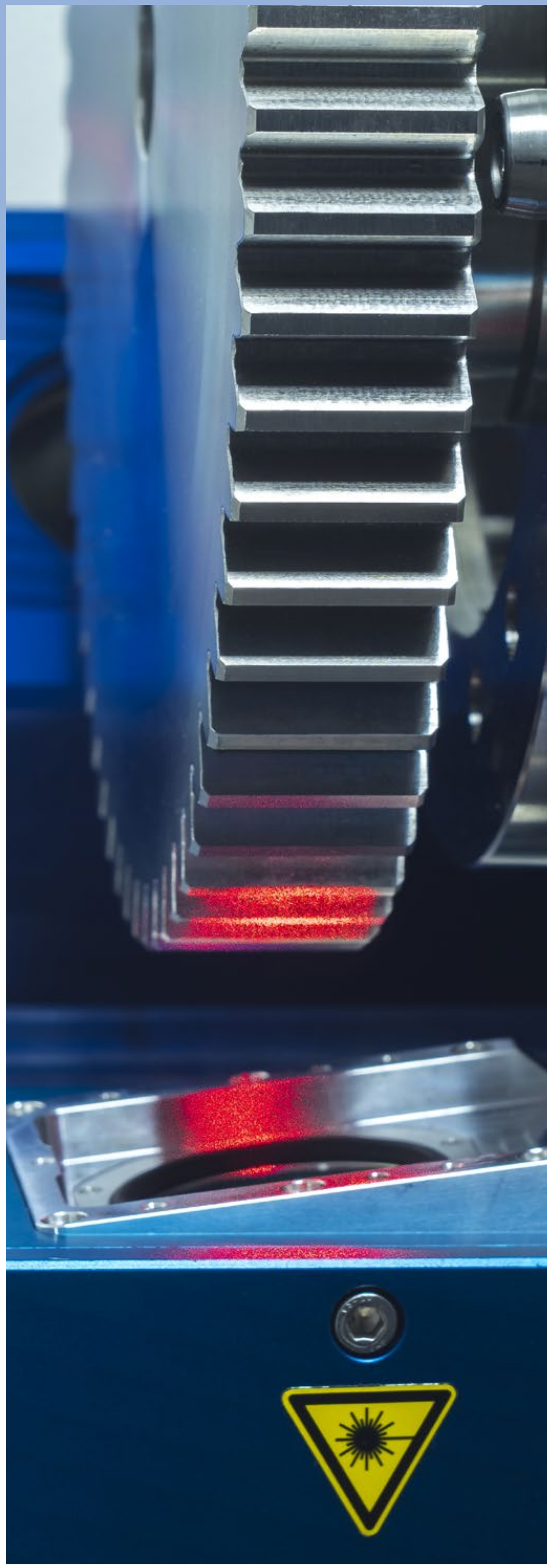
- Topography measurement of precision parts
- Measurement field size: 30 × 30 mm², can be scaled to suit specific applications
- Measurement accuracy: axial < 1 µm, lateral < 10 µm, depending on size of image field
- Measurement time: < 0.1 s up to 3D images with 10 million points
- Flexible working distance up to approx. 300 mm, mechanical focusing eliminated

GEAR MEASUREMENT

- 100% inspection of entire gear in just a few minutes
- Single spot measurement accuracy < 1 µm
- Spur and helical gears captured
- Active suppression of multiple reflections on the gear flanks
- Contactless measurement, even on moving objects

DYNAMIC DEFORMATION MEASUREMENT

- Temporally resolved imaging measurements with a frame rate of up to 1 kHz
- Image field of 10 × 10 mm²
- Measurement accuracy < 0.5 µm
- Non-contact and marker-free up to 1000 °C
- Strain-controlled short cycle strength analysis, load measurement and crack assessment
- Standard-compliant fatigue testing in just one hour of measurement time
- Electronic Speckle Pattern Interferometry (ESPI)



< Machine tools need to function with accuracy down to the micrometer – pushing them to the limits of their capabilities. The wireless 3D sensor HoloPort is the first sensor that can map the entire topography of components in the machine tool itself to a fraction of a micrometer.

GROUP **GEOMETRICAL INLINE MEASUREMENT SYSTEMS**

Interferometry in machine tools

Precision components must be produced with an accuracy of a few micrometers. Modern processing machines are reaching the limits of their capabilities. A new portable optical sensor from Fraunhofer IPM ensures the component quality needed – the HoloPort sensor maps the entire surface of 3D structures with accuracy down to the micrometer in the machine tool itself.

Precision components often need to be manufactured with a level of accuracy that even cutting-edge processing machines are unable to reliably deliver. Varying trajectories, light wear to tools, or errors in the internal calibration of sensors can lead to component geometries which lie outside of the specifications. Today, precision is generally ensured using tactile methods carried out with coordinate measuring machines in separate measuring rooms. The process is slow and complicated, and only random samples are possible. Before any deviations can be rectified, the workpiece must be repositioned in the machine. Fraunhofer IPM's new wireless optical sensor HoloPort offers a solution. HoloPort maps the entire component surface in the machine tool itself immediately after processing. The sensor is designed so that the spindle can grip it like a tool between two processing steps, enabling the contactless capturing of surface data without the need for any additional setup. Its interferometric accuracy even makes direct control of the machine tool possible for the first time. Development was financed by the foundation Baden-Württemberg Stiftung gGmbH as part of the Holo-Cut research project.

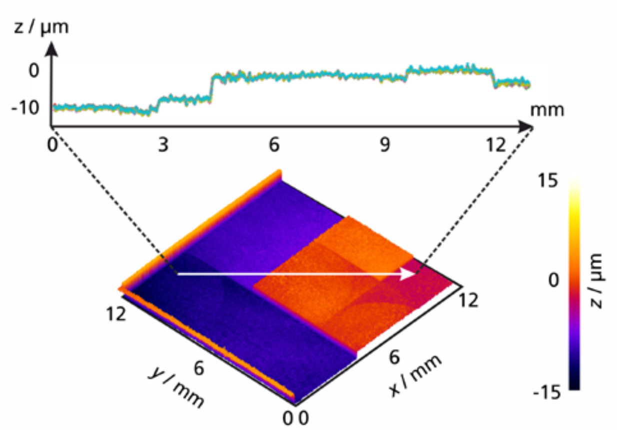
Complete quality control in the manufacturing process
HoloPort provides contactless, highly accurate measurements and operates so quickly and robustly that it can be integrated directly into the machine tool. The workpiece remains in place and the measurement data can be fed directly into a control loop for rectifying any deviations. HoloPort makes true 100-percent quality control in the manufacturing process possible for the first time. The sensor uses multiwavelength digital holography for inline 3D measurement and its axial length is no greater than that of a standard milling tool. It has an integrated energy storage unit and allows for wireless control and processing. The frequency-stabilized lasers needed for the multiwavelength digital holography, as well as the signal generation and processing systems, are integrated directly into the compact sensor head to make wireless operation possible.

The system maps the topography even of rough object surfaces with interferometric accuracy. This means that the milling parameters and trajectory as well as the wear to the tool can be monitored and optimized via a control loop. All relevant dimensions and surface parameters are available within a fraction of a second. HoloPort offers a level of reproducibility better than one micrometer for height measurements. Real-time inspection means that the manufacturing process can be monitored and the quality of every individual workpiece is 100-percent guaranteed. Another advantage of HoloPort is that it can be integrated into existing production processes without significant expense – as it is used in the machine tool itself, costly handling processes can be dispensed with almost entirely.

In **MULTIWAVELENGTH DIGITAL HOLOGRAPHY**, the phase information in the light is recorded in addition to the spatial intensity distribution of the light that is usually recorded photographically. A coherent light source – typically a laser – is required in order to do this. When the surface of a test specimen is illuminated using laser light, its shape is stored in the phase distribution of the backscattered light wave. Using interferometric recording and subsequent digital reconstruction, this information is made accessible and can be used to perform three-dimensional measurements of surfaces. The fundamental principle underlying holography dates back to an invention designed by Dennis Gabor in 1948, for which he was awarded the Nobel Prize in Physics in 1971.

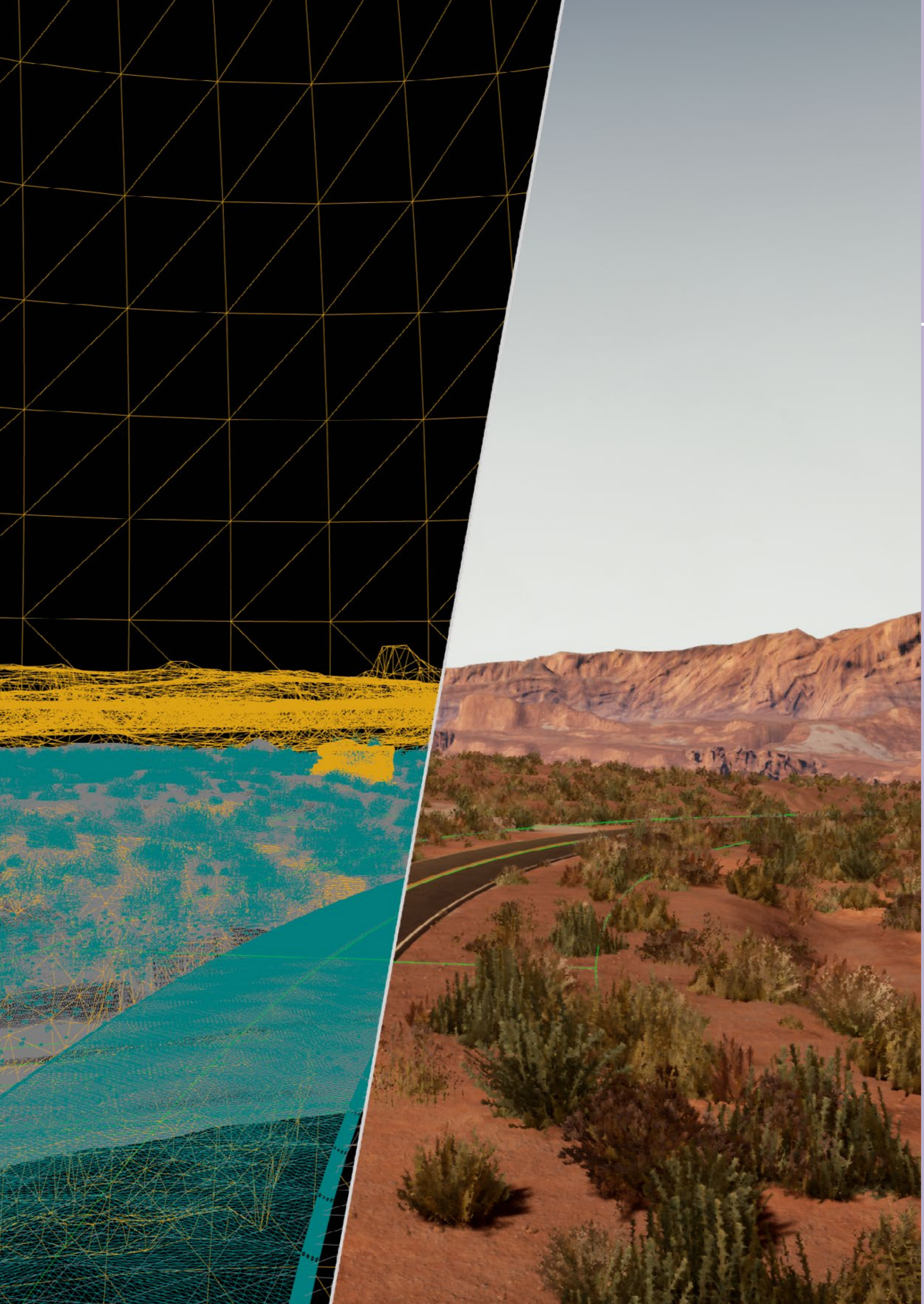
Topography analysis in real time
The illustration to the right shows a casing cover to demonstrate the impressive accuracy with which HoloPort comprehensively maps both the depth and surface roughness of individual milling marks. Typically, 2D profile sections are used for characterizing the surface and therefore for inspecting the results of the milling. However, these 2D sections only provide a very limited description of the surface and are not sufficient for characterizing ridges or randomly occurring structural elements, for example. A number of standards address 2D surface analysis (ISO 3274, ISO 11562, ISO 13565-1, ISO 4287, ISO 4288, ISO 1365-2). The HoloPort sensor makes it possible to comprehensively analyze the surface topography measured, which in turn enables function-oriented and structure-oriented 3D analysis of the surface in accordance with the ISO 25178 standards. These standards define the 3D parameters Sa, Sq and Sz based on the established 2D parameters Ra, Rq and Rz.

Automated inline inspection
The portable sensor head HoloPort could be the key to enabling fully automated inline inspection of highly precise components on many manufacturing lines. As complicated handling processes are no longer necessary, the sensor also cuts costs significantly. It is designed so that it can be gripped in the machine tool directly by the spindle in the same way as a tool. This reduces the overall inspection costs for the process.



The HoloPort sensor comprehensively maps the surface and depth of milling marks. This graph illustrates the high level of measuring accuracy based on ten measurements of the surface data.

Dr Alexander Bertz, P + 49 761 8857 - 362, alexander.bertz@ipm.fraunhofer.de



"We are increasing the functional range of laser scanners for use in the air and underwater."

In the "Object and Shape Detection" business unit, we serve the entire process chain for mapping, analyzing and visualizing the 3D geometries and positions of objects. For this purpose, we not only develop laser scanners, but also custom-made lighting and camera systems. These devices are able to perform measurements with high levels of speed and precision, particularly from moving platforms. Measurement data are evaluated in a fully automated process and interpreted by specially developed software. To this end, we employ techniques from the field of artificial intelligence (AI), such as deep learning. Data that are edited and visualized for specific applications provide experts with a sound basis for decision-making, for instance where the planning of infrastructure is concerned.

We focus specifically on speed, robustness and long service life of the systems. Objects and shapes are mapped three-dimensionally with a wide range of sizes covered – from a few centimeters to a scale of some 100 meters. The measurement systems are in use worldwide, their tasks ranging from monitoring rail infrastructure to surveying road surfaces. New areas of application include mobile data collection both from the air and underwater.

CONTACT

Prof Dr Alexander Reiterer
Head of Department
P +49 761 8857-183
alexander.reiterer@
ipm.fraunhofer.de

Group **Mobile Terrestrial Scanning**

- Rail systems
- Road systems
- Systems for meteorological applications (incl. wind LiDAR)
- Rapid and robust laser scanners
- Software for data interpretation

Group **Airborne and Underwater Scanning**

- Systems for unmanned aerial vehicles
- Systems for underwater applications
- Miniaturization of measurement systems
- Systems based on low-cost and consumer products (incl. smartphones)
- Software for data interpretation

Group **Smart Data Visualization**

- Real-time visualization of spatial data
- Smart data concentration
- Creation of synthetic measurement data (incl. for machine learning)
- Flexible function libraries
- Platform-independent systems

< After data acquisition and processing, the next logical step in the system chain is the visualization of measurement data.

BUSINESS UNIT **OBJECT AND SHAPE DETECTION**

GROUP **MOBILE TERRESTRIAL SCANNING**

Prof Dr Alexander Reiterer, P +49 761 8857 - 183, alexander.reiterer@ipm.fraunhofer.de

The research focus of the group is the development of time-of-flight measurement-based optical measurement systems for mobile use on rail and road vehicles. The systems determine distances to objects with great speed and accuracy. Combined with a scanning unit, they can also capture three-dimensional object geometries. Mobile laser scanning requires the measurement system to detect positions and locations with high accuracy. To achieve this, the group is developing special camera-based techniques which – either when used in isolation or in combination with conventional inertial sensors – allow data to be assigned to a fixed system of local or global coordinates. The group is additionally conducting research on the automated interpretation of 2D and 3D data using self-learning algorithms (incl. deep learning).

Group Manager: Prof Dr Alexander Reiterer

>> High-speed laser scanners generate detailed point clouds of the environment. A quickly rotating deflection unit is at the heart of such systems.

EXPERTISE

Time-of-flight measurement systems for recording distances with submillimeter accuracy | Rapid laser scanners capturing given environments | Robust laser scanners for mobile platforms on road and rail measurement vehicles

APPLICATIONS

Scanning and camera systems for surveying and monitoring rail infrastructure such as tracks, platforms, and overhead wires | Systems for fast and precise detection of road surfaces and for tunnel inspection (crack detection in the millimeter range) | Systems on mobile platforms and driverless vehicles for surveying difficult-to-access objects – these may be integrated, for example, into mobile robotic systems | Fully automated analysis and classification of 2D and 3D data using deep learning algorithms (e.g. for analyzing road infrastructure)

SPECIFICATIONS

RAIL SYSTEMS

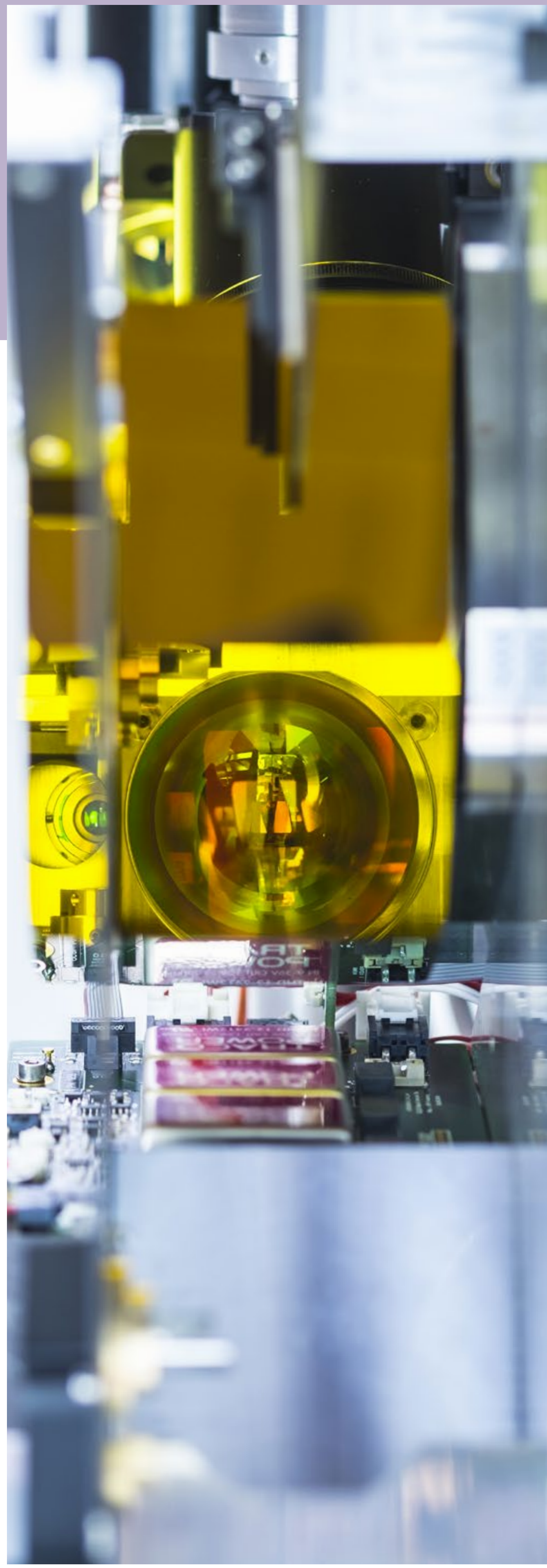
- Overhead wire surveying at speeds of up to 250 km/h
- Railway line clearance monitoring with an accuracy of 3 mm
- Environment scanning with up to 800 profiles per second
- Track profile measurement with an accuracy of 0.3 mm

ROAD SYSTEMS

- Measuring transverse evenness of roads with an accuracy of 0.3 mm
- Mapping of 2 million measuring points per second
- Surveying road corridors of up to 300 m in width with an accuracy of 3 mm
- Detecting cracks in road surfaces at driving speeds of 80 km/h with a resolution of 1 mm

AUTOMATED DATA INTERPRETATION

- Interpreting 2D and 3D measurement data fully automatically, incl. by means of deep learning
- Implementing cloud-based solutions for data processing
- Building comprehensive training datasets for the automated training of algorithms



< Small cracks in the road surface are often the first warning sign of more serious damage. To keep maintenance costs down, any such damage must be identified and repaired as early as possible.

GROUP **MOBILE TERRESTRIAL SCANNING**

A close-up inspection: Detecting cracks in road surfaces

Laser scanners are increasingly being used to measure the evenness of road surfaces. But additional cameras are still used to detect structural damage on a smaller scale. Fraunhofer IPM has now upgraded its Pavement Profile Scanner (PPS) to create the PPS Plus, which provides not just 3D geometric information but also – for the first time – photo-realistic images of the road's surface, showing cracks and other structures down to the millimeter. The 2D images are generated not by a camera but by an additional laser for measuring intensity.

One of the key considerations in road maintenance, alongside the elevation profile, is surface damage such as patching, potholes or fine cracks. Detecting this damage early on can make it possible to prevent more serious and expensive damage. Fraunhofer IPM's original PPS road scanner, on which the new model is based, is the only laser-based measurement system to be approved by the German Federal Highway Research Institute (BASt) for measuring transverse evenness on roads. The device offers cutting-edge levels of precision and resolution for road surface measurements. The scanner is the size of a shoebox and is mounted on a survey vehicle to scan the road surface with an eye-safe laser beam across a width of approximately four meters. The distance to the road surface is determined with sub-millimeter based on phase shift measurement. The laser uses a rotating polygon mirror to scan the surface perpendicular to the direction of travel of the vehicle, generating 800 profiles per second. Each profile consists of as many as 900 measuring points, depending on the measuring frequency selected. This allows the PPS to generate a detailed 3D elevation profile of the road surface. However, at speeds of 80 km/h, the distance between measuring points in the direction of travel is still around 28 mm, while this distance in the perpendicular direction is 4.5 mm. Many types of damage are visible at this resolution – but for detecting cracks merely a few millimeters large, it is not enough.

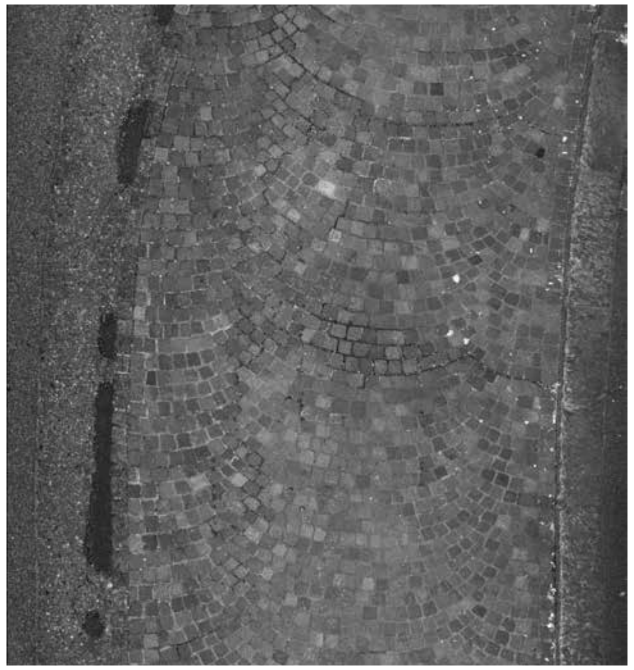
Generating photos without a camera

To detect such small-scale damage, researchers at Fraunhofer IPM have now upgraded the PPS using patented technology. The PPS Plus features an additional laser instead of the cameras usually used for crack detection. It works by measuring the intensity of the backscattered light. This information is used to generate a photo-realistic image with a resolution in the millimeter range capable of showing even minuscule damage. The patented 2D measuring setup includes newly developed optical, mechanical and detection systems which were synchronized with the laser deflection apparatus (polygon mirror), detection lens and detection unit of the 3D laser scanner.

Measuring the intensity of a backscattered laser beam offers a number of advantages over the camera technology conventionally used for crack detection. Cameras require additional active illumination, which means installing bulky equipment on the survey vehicles. The PPS Plus integrates both a distance and an intensity scanner to allow a compact optical setup and flexible system design for mounting on a range of mobile platforms. This means that the system can perform reproducible measurements in moving traffic without the need for road closures. The use of a laser generates uniformly high-resolution images regardless of the ambient light conditions. This is virtually impossible to achieve with cameras since they require additional lighting to balance out light differences along the road, but such uniformity is essential for automated and standardized analysis. And the variety of colors found on the road surface, from the dark asphalt to the light painted markings, is problematic for camera but not for intensity measurements. These measurements eliminate the need to combine individual camera images and then merge scanner and camera data – a time-consuming process.

COMBINED LASER INTENSITY AND DISTANCE MEASUREMENTS: In conventional laser distance measurement, the intensity of the backscattered light is always measured, too. However, the optimal wavelength, measuring frequency and focal spot size are different for distance measurement and intensity measurement. To generate camera-quality gray-level images, the intensity measurements must be performed with a separate laser which allows these parameters to be freely selected. With the PPS Plus, both lasers are deflected using a single scan mirror, ensuring that the geometrical and image data are precisely aligned. This means that the ability to correctly classify spatial characteristics is intrinsic to the system.

The wavelength of the laser used for the intensity measurements was selected to give the optimal image contrast. While the distance scanner's measuring frequency of 1 MHz is sufficiently fast, a measuring frequency of around 4 MHz is needed for the intensity measurements based on a driving speed of 80 km/h. This results in a spatial resolution of around 1 mm over the scanning range of 4 meters. To obtain more detailed measurements also in the direction of travel, the second laser beam is expanded in the direction of travel and measured with multiple detectors at the same time. This increases the resolution in the direction of travel without the need to change the mechanical scanning frequency. Four PPS Plus road surface scanners are already in use and three more are currently being prepared for deployment.



The Pavement Profile Scanner generates photo-realistic images of the road surface which show structural features measuring just a few millimeters.

Prof Dr Alexander Reiterer, P +49 761 8857 - 183, alexander.reiterer@ipm.fraunhofer.de

GROUP **AIRBORNE AND UNDERWATER SCANNING**

Simon Stemmler, P +49 761 8857 - 211, simon.stemmler@ipm.fraunhofer.de

The research focus of the group is the development of optical measurement systems for use on drones and underwater vehicles. The systems use time-of-flight measurement techniques to measure distances to objects with high accuracy and to generate three-dimensional data on structures in combination with cameras. Thanks to an extremely lightweight construction and miniaturization, the measurement systems can be used on small aerial vehicles. Another research focus is the development of complete systems for capturing 3D data in turbid media. Amongst other things, these systems enable condition monitoring of underwater structures such as offshore wind farms. The group is also working to develop lean 3D measurement technology solutions based on low-cost and consumer products, e.g. smartphones.

Group Manager: Simon Stemmler

>> Time-of-flight measurement is the method of choice for underwater laser scanning, where particularly robust systems are required.

EXPERTISE

Time-of-flight measurement system for surveying distances with subcentimeter accuracy | Lightweight laser scanners for installation on flying platforms | Special laser scanners for scanning underwater environments | Use of consumer and low-cost sensor technology for a wide range of applications

APPLICATIONS

Scanners and camera systems on unmanned aerial vehicles (UAV) for surveying and monitoring construction sites, bridges and areas of vegetation | Scanners on underwater robots (remotely operated vehicles, ROV) for surveying infrastructural elements such as pipeline foundations and offshore wind farms | Sensors based on low-cost and consumer sensor technology to enable efficient and affordable object capture, e.g. on construction sites | Special software for data interpretation, e.g. for assessing the condition of vegetation

SPECIFICATIONS

AIRBORNE SYSTEMS

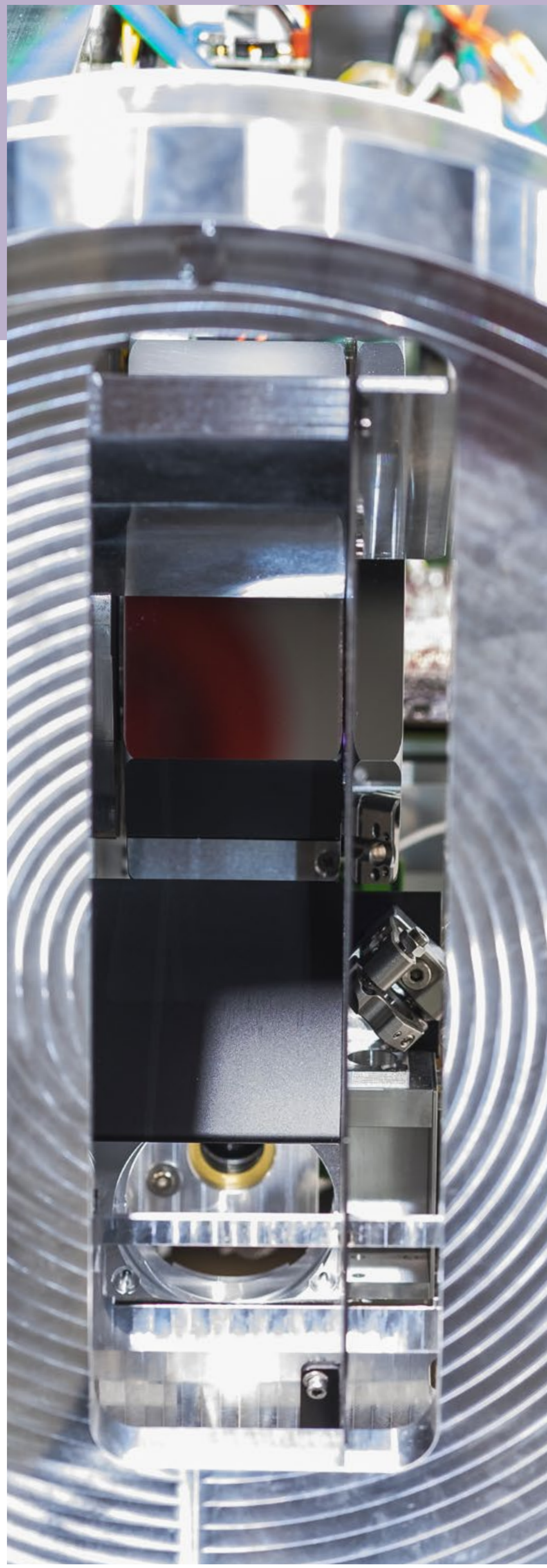
- Measurement systems (laser scanner and cameras) weighing under 2.5 kg
- Measurement precision 1 cm
- Typical measurement distances of up to 100 m
- Measurement frequencies of up to 60 kHz
- Position measurement using visual odometry as well as positioning and orientation systems

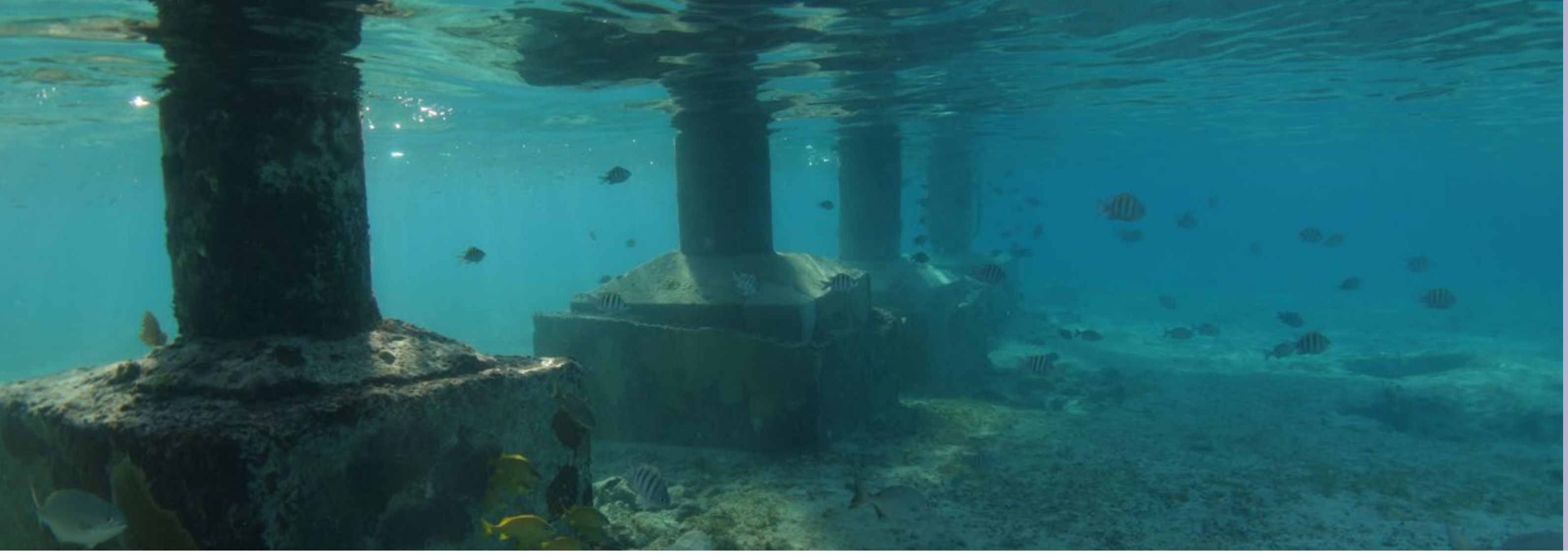
UNDERWATER MEASUREMENT SYSTEMS

- 3D surveying with subcentimeter resolution, even in turbid water
- Measurements irrespective of light conditions and depth
- Measurement frequency up to 50 kHz
- Stationary and mobile surveying

DATA PREPARATION

- Fusion of 3D and 2D data incl. positioning (texturizing)
- Derivation of metadata from texturized 3D data
- Automated data interpretation, e.g. based on "Deep Learning"
- Automation of surveying tasks





< Inspecting underwater structures is complex and dangerous. The intention is for laser scanners to take on the task of monitoring such constructions in future. They can measure with greater precision and reliability than the systems employed to date.

GROUP **AIRBORNE AND UNDERWATER SCANNING**

Going deep: Underwater laser scanning

At present, underwater structures are generally inspected by divers – sometimes at very great risk. True geometric condition monitoring is virtually non-existent. However, Fraunhofer IPM has now been able to show that 3D measurements can be taken underwater with the help of laser scanners. The long-term goal is to develop a LiDAR-based measurement system for acquiring 3D data on underwater structures.

Throughout 2017, well over a thousand wind turbines spun off the German coasts while some 600 drilling platforms produced crude oil across the globe. Large parts of these structures are submerged in water and are exposed to extremely harsh environmental conditions. The importance of monitoring the condition of such structures was dramatically highlighted by the Deepwater Horizon drilling rig blowout in 2010. Large-scale dams and tidal range power plants pose similarly high risks. Measurement technology can help to make the inspection of such plants accurate, efficient, and cost-effective. The availability of innovative underwater measurement technology is also an advantage where mapping inland waters and shipbuilding are concerned. It allows navigation channels to be surveyed with greater speed and reliability, and ship retrofitting can be planned more efficiently.

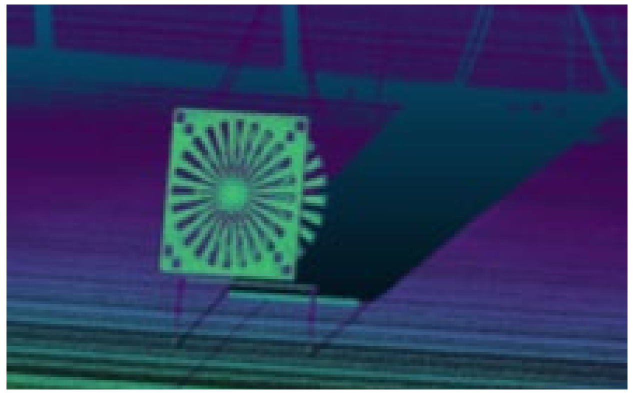
LiDAR outperforms sonar

Typically, underwater structures are monitored using cameras. The images and videos taken support the visual inspections performed by divers. However, the poor light conditions mean that the quality and scope of these images are limited. Images are analyzed manually – a procedure that provides no objective measurement parameters. Geometric dimensions, such as those concerning the topography of ocean floors or those used to determine the position of objects, can only be derived from these images using photogrammetric methods, which are very labor and cost-intensive. Data on large-scale structures are commonly gathered using acoustic measurement systems such as sonar. The disadvantage of this approach is that sonar measurements are comparatively slow and inaccurate. Even at close range, scanning sonar systems only deliver resolutions of a few centimeters. Where condition monitoring is concerned, however, it is necessary to be able to detect deformations down to the millimeter, since these provide early indications of damage. Thanks to their shorter wavelengths and their constant, high propagation velocity, optical techniques achieve fundamentally greater accuracy and measurement speeds than their acoustic counterparts. Here, the time-of-flight method is the most suitable for use underwater. For the DeepInspect project funded by the Fraunhofer-Gesellschaft, Fraunhofer IPM is collaborating with Fraunhofer IGP on an underwater laser scanner that employs this method and that is intended to enable true 3D data capture on submerged structures.

UNDERWATER TIME-OF-FLIGHT MEASUREMENT The time-of-flight method is an extremely accurate optical method for measuring distance. A short laser pulse is emitted, backscattered by the measurement object and picked up by a detector. The distance to the object is given by the propagation delay needed for the pulse to travel from the laser source to the detector. If the laser beam is deflected via a continually oscillating or rotating mirror, 3D pixel information can be deduced from the mirror position and the propagation delay of the light (scanner). In the optically dense medium of water, light travels more slowly than in the atmosphere – which benefits measurement accuracy. At the same time, poor visibility, suspended particles, salinity, and the resulting reflections complicate the measurements.

Digital compensation for light scattering

Performing time-of-flight measurements in turbid water presents scientists with new challenges, since different physical laws apply to the behavior of light underwater than in the atmosphere: Beams of light are very strongly attenuated by water, and scattered particles make it more difficult to interpret the actual measurement signal. It was already clear in the preliminary stages of the project that the problem of light attenuation is solvable, since laser pulses can be adequately reflected over several kilometers where light propagation is undisturbed. A laser range finder, which can measure over a kilometer on land, will still achieve a sufficient signal level even when light is attenuated to one percent over a measurement distance of 100 meters. Such measurement ranges are adequate for the majority of underwater measuring tasks. Overcoming light scattering proves more of a challenge, however: Particles suspended in the water reflect part of the measurement beam. The scattered signal of all objects in the measurement volume reach the detector, although only the signal from the furthermost measurement object is desired. It is therefore necessary to isolate superfluous signals from the object's signal. The key to doing this is signal digitization: Rapid analog-to-digital converters assign a specific propagation delay, and thus a specific range, to the digitized signals. This technology is already employed in terrestrial laser scanners, for instance to eliminate interference from vegetation. Using real-time digitization and subsequent signal processing, the team has now been able to demonstrate that this approach is even successful with continually occurring obstructions.



Under ideal conditions in the testing tank, the underwater laser scanner can measure with an accuracy of approximately four millimeters (a test object is shown here).

A prototype was used to perform successful test measurements in a specially-designed underwater measurement tank. In clear water, a measurement accuracy of four millimeters was achieved over a distance of up to ten meters. The measurement system, which is cased in a watertight pressure housing, will be tested in the sea in spring 2019.

Simon Stemmler, P +49 761 8857-211, simon.stemmler@ipm.fraunhofer.de

BUSINESS UNIT **OBJECT AND SHAPE DETECTION**

GROUP **SMART DATA VISUALIZATION**

Prof Christoph Müller, P +49 761 8857 - 236, christoph.mueller@ipm.fraunhofer.de

The research focus of the group is the customized visualization of measurement data. Smart data visualization provides the foundations for rapidly gathering data on complex situations and deriving targeted actions from this information. In any situation where processes are adjusted interactively, measurement results must be visualized in real time. Depending on the application, an enormous variety of visualization options and suitable platforms may be required to do this. In-depth knowledge of all the underlying data offers the potential for more: For example, synthetic training data for AI-based object detection can be generated directly within measurement data. Or measurement data can be reduced during acquisition for targeted evaluation. This is particularly important if data visualization is required for mobile environments where performance is limited.

Group Manager: Prof Christoph Müller

>> Synthetic image data are suitable for making the training of artificial neural networks more efficient. The structural elements of an object (m.) can be used to generate simulated camera images (above) or a classified scene (below).

EXPERTISE

Algorithms and methods for smart data concentration to facilitate the optimized handling of extensive measurement data | Extended operational range of both established and prospective measurement technology via real-time visualization of spatial data | Expertise in rendering images from 3D models to generate synthetic measurement data

APPLICATIONS

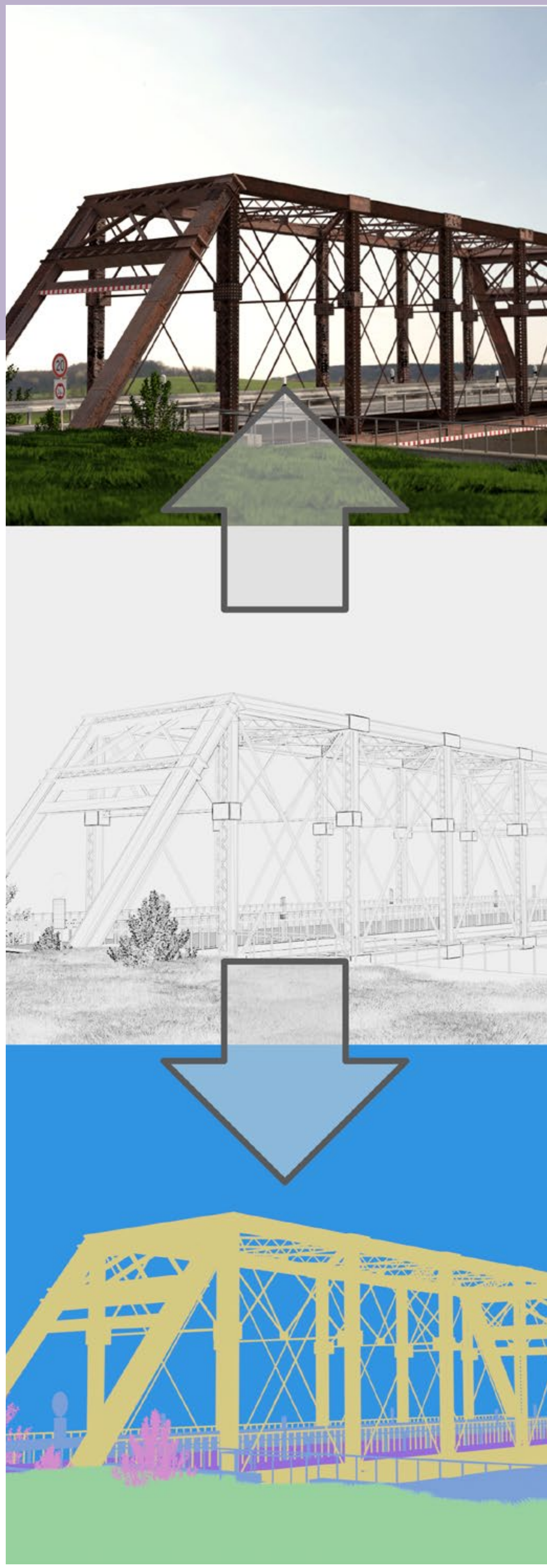
Quality and completeness controls during data acquisition (e.g. with drone-based scanners) by visualization on mobile devices | Interactive applications for navigating edited measurement data to support complex analyses and decision-making processes (e.g. in medical applications) | Training data generated by automation for conditioning artificial neural networks, which allow measurement technology to be iteratively optimized for subsequent machine detection

SPECIFICATIONS

FLEXIBLE
- Real-time 3D visualization
- Point cloud depiction
- 3D data handling
- User interfaces

PLATFORM-INDEPENDENT, RUNS ON
- Desktop
- Android
- Web browser
- 80 percent common codebase

MODULAR STRUCTURE
- Software library



< Inspecting structures from the air using UAV based laser scanners – this visualization makes it easy to identify anomalies and correlations within the measurement data.

GROUP **SMART DATA VISUALIZATION**

Making measurement data intuitive: Visualization is key

Modern optical measurement systems can map the 3D geometry and position of objects quickly and accurately. It is increasingly common for the interpretation of these measurement data to be automated. Users at the end of the chain now expect measurement results to be presented quickly and intuitively. To meet this demand, Fraunhofer IPM is boosting its research into methods for visualizing measurement data.

Complicated subject matter can be explained quickly and intuitively with suitable graphics. This goes for measurement technology, too – when results are presented as graphics, images or videos, users can interpret them more quickly and efficiently than point clouds, measurement curves or columns of figures. Modern computer graphics make it possible to quickly generate high-quality images and animations. The computer game industry in particular is driving progress in this area, setting technological standards and leading users to raise their expectations when it comes to visualization. And measurement technology needs to keep pace with these developments. Users expect measurement results to be available in real time and in an intuitive format, ultimately serving as an ergonomic tool for analysis and decision-making.

To make this possible, Fraunhofer IPM is working on a range of concepts and techniques for visualizing measurement data. This research has now been consolidated with the creation of the Smart Data Visualization Group. The MultiVIS project in cooperation with Furtwangen University (HFU) will receive five years of funding from the Fraunhofer-Gesellschaft as part of its Cooperation Program with Universities of Applied Sciences (UAS). Prof Christoph Müller of the HFU has been appointed as group leader, bringing a wealth of expertise and experience in data processing and visualization.

Data visualization on mobile devices

Surveying large structures such as traffic infrastructure or expanses of vegetation using laser scanners generates enormous quantities of data. The faster and more intuitively the results of the measurements are presented, the more useful they can be, in turn speeding up decision-making and guiding ongoing processes. It's essential that the data be automatically interpreted and visualized in real time. Vast point clouds can be advantageous when the aim is to depict the surroundings in as much detail as possible. But multidimensional data streams, for example containing 2D and 3D data, are a challenge for real-time processing. This requires specially designed algorithms and methods for data reduction, in particular when the end goal is to allow visualization of measurement data on mobile devices with limited bandwidth. This applies, among other things, to new developments in the fields of virtual reality (VR) and augmented reality (AR). To date, only a handful of isolated projects have tested these in connection with the visualization of measurement data. Solutions are needed for coupling measuring device hardware and visualization software for the individual device types. One such application that the group is already exploring is the visualization of measurement data for monitoring deformation processes in tunnel construction. To this end, Fraunhofer IPM is currently developing a novel multispectral scanner system for mapping geometry, surface structure and humidity. For communication between measurement service providers, civil engineers and construction workers, the measurement data will be made accessible via 3D glasses and displayed using AR instead of using conventional static diagrams or graphs.

SOFTWARE PLATFORMS FOR 3D VISUALIZATION OF POINT CLOUDS: Major device and software manufacturers have joined forces with research organizations to create the Point Cloud Library (PCL), an open-source research and development platform which provides a foundation for efficient analysis of 3D point clouds. Similarly, Fraunhofer IPM is setting up its own software platform – based on the 3D platform FUSEE developed by Prof Christoph Müller at the HFU – containing components for interactive interpretation and visualization of measurement data.

Synthetic training data for KNN

Fraunhofer IPM and the HFU have already developed strategies for real-time visualization of measurement data across a number of joint projects. With the Traxplorer project, for example, they created a real-time visualization software program which displays data generated by scanning railway lines. Special algorithms were developed to suit the specific configuration of the data – large volumes along a linear track. In the CloudVision project, students developed a software program which can be used on a mobile device for real-time depiction of laser scanner data captured by a UAV. The project RaVeNNA-4pi, funded by the German Federal Ministry of Education and Research (BMBF), aims to improve visualization of measurement data to aid in the endoscopic examination of bladder carcinomas. And at INATECH in Freiburg, a group led by Prof. Alexander Reiterer is working on strategies for automated data processing based on machine learning.

Visualizing a point cloud – the unsorted 3D coordinates (top of image) are converted into a closed 3D representation (bottom of image) by means of splatting and by computing the spatial orientation of each single point.

Photo-realistic computer-generated images are not just easier for users to interpret; such synthetic data can also assist the training of artificial neural networks (ANNs). Fraunhofer IPM is increasingly using ANNs to automatically identify and classify measurement data. The researchers believe that this holds major potential for making the training process more efficient over time.

Prof Christoph Müller, P +49 761 8857-236, christoph.mueller@ipm.fraunhofer.de

"We're using our expertise to open up new possibilities for measurement technology."

In its "Gas and Process Technology" business unit, Fraunhofer IPM develops and manufactures measuring and control systems to meet customer requirements. The main features of these systems are short measurement times, high precision and reliability, even in extreme conditions.

The expertise in the business unit includes laser spectroscopic methods for gas analysis, energy-efficient gas sensors, particle measuring technology, thermal sensors and systems as well as nonlinear optics and, as of late, quantum sensing. The scope of applications is massive – it extends from flue gas analysis and transport monitoring for food to sensors and systems for measuring very small temperature differentials.

Group **Integrated Sensor Systems**
- Gas sensitive materials
- Micro-optical components
- Miniaturized gas sensor systems

Group **Spectroscopy and Process Analytics**
- Spectroscopic analytics
- Optical systems
- Data evaluation methods

Group **Thermal Measurement Techniques and Systems**
- Custom-made microstructures
- Thermal measurement systems
- Simulation of physical processes

Group **Nonlinear Optics and Quantum Sensing**
- Nonlinear optics
- Laser absorption spectroscopy
- Quantum sensing

< Developed in the lab, deployed in the field – we specifically tailor optical techniques for use in diverse environments.

CONTACT

Prof Dr Jürgen Wöllenstein
Head of Department
P +49 761 8857-134
juergen.woellenstein@
ipm.fraunhofer.de

BUSINESS UNIT GAS AND PROCESS TECHNOLOGY

GROUP **INTEGRATED SENSOR SYSTEMS**

Dr Marie-Luise Bauersfeld, P +49 761 8857-290, marie-luise.bauersfeld@ipm.fraunhofer.de

The main focus of this group is the development of functional gas sensitive materials and surfaces, and miniaturized gas sensor systems. Gas sensor technology and electronics are combined in compact, low cost microsystems for this purpose.

Group Manager: Dr Marie-Luise Bauersfeld

>> Compact photoacoustic sensor system for carbon dioxide detection.

EXPERTISE

Customer-specific synthesis and processing of gas sensitive materials for specific applications | Micro-structured IR emitters as light sources in micro-optical sensors (MOEMS) | Development of low-cost, energy-efficient gas sensors for integration into wireless sensor networks or mobile devices

APPLICATIONS

Efficient air conditioning technology through selective detection of gases | Early detection of toxic gases | Food quality monitoring in food warehouses or during transportation | Gas sensors for smart applications, e.g. smart home

SPECIFICATIONS

GAS SENSITIVE MATERIALS

- Materials synthesis and processing, layers of a few nm to some µm, coatings of micro-structured substrates (MEMS)
- Semiconductor gas sensors: metal oxide layers such as SnO_2, WO_3 or $Cr_{2-x}Ti_xO_{3+z}$ with catalytic additives
- Colorimetric gas sensors, e.g. color change materials for CO, NO_2, NH_3 , H_2S, and volatile organic compounds (VOC)

MICRO-OPTICAL COMPONENTS

- IR emitters for a wavelength range of 5 to 12 µm, can be modulated if desired
- IR detectors (e.g. made of PbSe) for a wavelength range of 3 to 5 µm
- Diffractive optics, e.g. Fresnel lenses made of silicon or components for IR emitters

MINIATURIZED GAS SENSOR SYSTEMS

- Detection of gas concentrations from ppb to percent according to measurement principle applied; modular systems by combining various sensor principles
- Sensor technology for energy self-sufficient systems with wireless communication
- Photoacoustic systems, filter photometers and miniaturized gas chromatography systems

< Colorimetric gas sensors could ultimately complement the smoke detectors commonly used today. The technology can be applied to many different fields.

GROUP **INTEGRATED SENSOR SYSTEMS**

Colorimetric sensors: Colors signal toxic gases

In the future, innovative sensor systems will be capable of rapid, selective measurements of toxic gases based on the color change principle. Fraunhofer IPM is pursuing several research projects investigating materials and system concepts for colorimetric gas sensors. As part of this work, a miniaturized sensor platform is being constructed for tasks including fire gas detection.

There is no noise or odor that announces the onset of a fire. Toxic gases such as carbon monoxide (CO) and nitrogen oxide (NO_2) are produced before smoke becomes visible, and just a few breaths of these can be fatal. Despite this, standard smoke detectors do not react to such gases and only sound an alarm once smoke particles are released. Fire gas sensors can help to detect fires at an earlier stage. To date, however, these gas detectors – usually semiconductor gas sensors or infrared sensors – are virtually unheard of in private households. Depending on the technology used, they are too expensive, have a limited lifespan, consume too much power or do not reliably differentiate between different gases. Color-changing sensors put early fire detection on an entirely new technological footing, which opens up a wide range of other potential applications beyond fire gas detection – in essence, anywhere where compact, energy-efficient, durable gas detectors are required.

Sensitive, selective fire gas detection

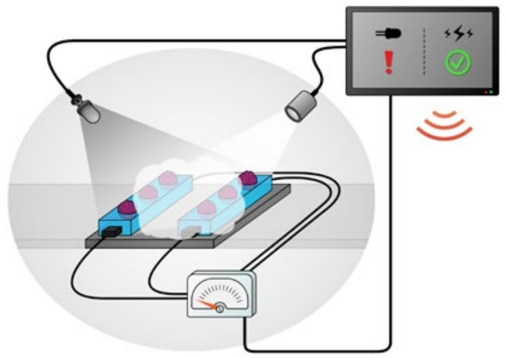
Color-changing sensors are characterized by a high degree of selectivity and sensitivity, something that is particularly crucial where fire gas detection is concerned. The gas-sensitive dye only reacts with a specific gas and, thanks to the low cross-sensitivity of colorimetric sensors, false alarms are rare. At the same time, gas sensors that operate on the color change principle work with detectable levels as low as the ppm (parts per million, 10^{-6}) range, as Fraunhofer IPM was able to demonstrate using the example of the fire gases CO and NO_2. A variety of sensor concepts are possible. For example, the researchers have combined specially designed sensor materials with optical and electrical measurement techniques. Porous substrate particles measuring just a few micrometers in diameter are coated with a dye and combined to create sensor particles. These sensor particles are constructed as so-called mole-hill structures embedded within a matrix of electrically conductive polymers, which are assembled as electrode structures. This sensor design ensures a favorable surface-to-volume ratio and facilitates the target gas's access to the gas-sensitive dye. Any light falling on the sensor particles is diffusely reflected. The reaction with the gas causes a change in the intensity of the reflected light, which is registered by a photodetector. parallel to the optical color change reading, a referenced electrical measurement of the material properties takes place in the same system. As a result, changes in environmental influences – such as high levels of atmospheric humidity or contamination from dust and fat – can be detected and offset during signal processing.

DETECTING GAS BY MEANS OF COLOR CHANGES: The presence of gases can be verified using chemical reactions that trigger color change in a specially selected sensor dye. This change in color is triggered as soon as a target gas molecule hits the gasochromic layer. Such reactions follow the lock-and-key principle – only the indicator molecule will trigger the color change, while all other gases barely react or do not react at all. The principle gained currency as early as 1937 with the introduction of Dräger tubes, which were also used to detect the presence of CO. These tubes are not suitable for everyday sensors, however, as they are only designed for single use.

Application-specific sensor concepts

Colorimetric gas sensors are of interest for a wide variety of applications. In addition to fire gas detection, Fraunhofer IPM is developing sensor systems for the detection of ammonia (NH_3), ethanol (C_2H_6O), formaldehyde (CH_2O), and hydrogen sulfide (H_2S). This involves adapting the polymer/dye structures, system configuration and readout units to each specific application. As an alternative to mole-hill structures, the dyes can, for example, be embedded in polymer matrices. Readings are then performed optically using simple transmission measurement. During this process, LED light is directed through a waveguide by total internal reflection and is focused on a photodetector on the exit side. Any color change in the gas-sensitive material leads to a measurable change in absorption. In a patented configuration, Fraunhofer IPM has optimized simple transmission measurement such that its sensitivity is comparable with waveguide-based sensors. The key to achieving this lies in folding the flexible sensor substrate. Doing so means that the light beam passes through the gas-sensitive layer multiple times, allowing the absorption path to increase in size while the sensor remains small. Large quantities of these sensors can be manufactured cheaply using roll-to-roll processing.

The team is also working on integrating the polymer/dye matrix into a sensor film. The intention is for such films to become part of standard protective equipment, where they will take the form of credit card-sized sensors that indicate critical gas concentrations, for example by emitting an audible signal. Color change can, however, also be registered by eye without any signal conversion. A visible change in color is of particular interest for applications in the food industry and food logistics sector, in air conditioning and safety technology, and in medicine. Irrespective of the application, one important feature is that gas detection based on the color change principle functions at room temperature. The technology is therefore fundamentally well suited to future integration in smart devices.



Substrate particles coated with a sensor dye are embedded in a polymer. These mole-hill structures ensure a good intake of target gas thanks to their large surface area, which ensures a high degree of sensitivity.

Dr Marie-Luise Bauersfeld, P +49 761 8857 - 290, marie-luise.bauersfeld@ipm.fraunhofer.de

GROUP **SPECTROSCOPY AND PROCESS ANALYTICS**

Dr Raimund Brunner, P +49 761 8857-310, raimund.brunner@ipm.fraunhofer.de

The group's research focuses on developing spectroscopy systems for the detection and analysis of liquids and gases. Its work is founded on many years of experience in exhaust gas and fuel gas measurement technology. Methods including Raman, ATR and laser spectroscopy are used. The group's activities range from lab investigations to prototype development to product engineering and support with commencing series production.

Group Manager: Dr Raimund Brunner

>>Gas leaks in industrial facilities can cause significant damage. Laser spectroscopy and infrared measurement techniques enable reliable leak monitoring in large-scale facilities.

EXPERTISE

Infrared and laser spectrometers used as the basis of measurement systems for gas and liquid analytics | Simulations and analysis methods for developing special optical assemblies and electronics modules | Characterization of optical components using Fourier and X-ray spectroscopy | Degradation and stability testing

APPLICATIONS

Spectrometer modules for quality control in drinks manufacturing or chemical processes | Rapid gas analyzers in complex gas matrices for exhaust gas test benches used in engine development and for performing calorific value checks in natural gas line systems | Leak detection using laser spectroscopy and infrared imaging measurement technology for safety monitoring and industrial facilities

SPECIFICATIONS

SPECTROSCOPY ANALYTICS

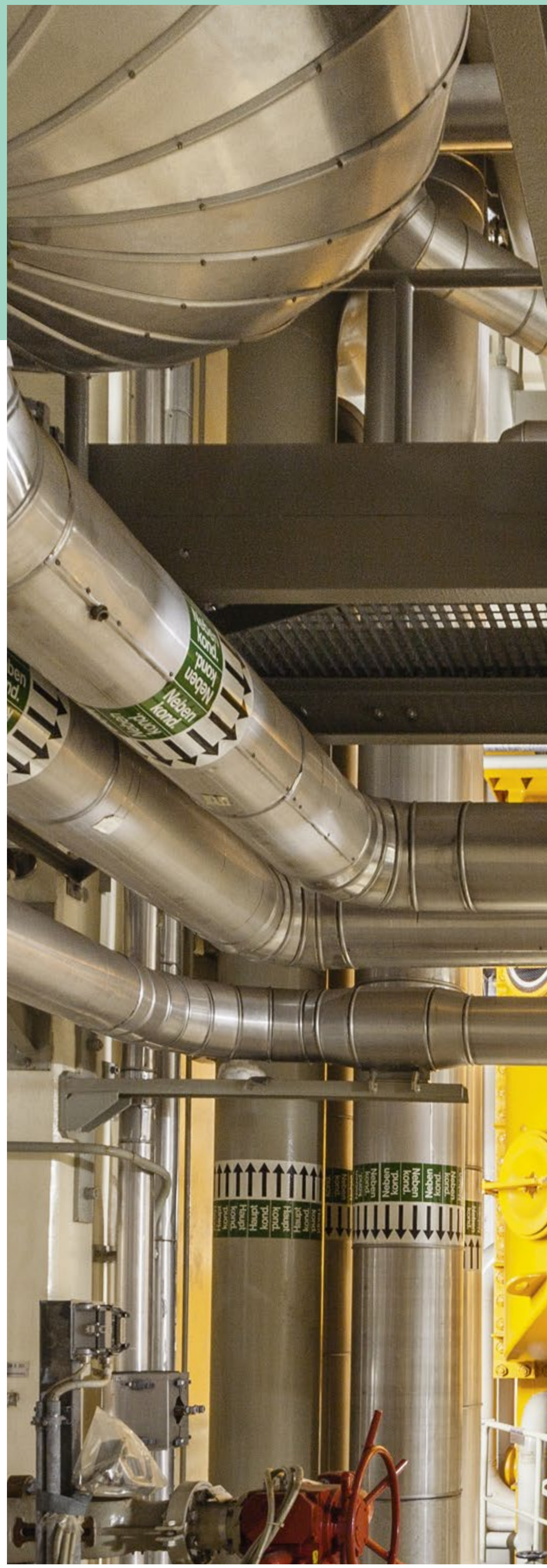
- Optical trace gas analyzers based on laser spectroscopy: sensitivity of 10 ppb for N_2O and NH_3, and 10 ppm for O_2
- Raman spectroscopy: chemometrics and analysis of liquids, cells and gases
- ATR spectroscopy: measurement of gases dissolved in liquids down to the ppm range
- Photoacoustic measurement methods, individual acoustic resonator tuning

OPTICAL SYSTEMS

- Simulations: optics, mechanics, flow, electronics
- Long-path absorption cells (White, Herriott and single-pass configurations): light path of 0.1 to 15 m, up to 200 °C
- Special optics: EUV diffraction gratings, laser packages including collimators, reference systems
- In-situ measurement methods, backscattering detection

EVALUATION METHODS

- Chemometric methods for analyzing measurement data
- Determining the measurement accuracy and reliability of gas sensors and laser systems under different conditions
- Modeling as a basis for linearization and calibration-free spectroscopy



< Around a third of climate-damaging nitrous oxide emissions can be traced back to the use of nitrogen fertilizers.

GROUP **SPECTROSCOPY AND PROCESS ANALYTICS**

Sensors to improve agricultural efficiency

Crop yields need to keep pace with the growth of world population. Nitrogen-based fertilizers play an important part in this. Each year, over 120 million metric tons of nitrogen are spread onto fields across the globe. Less than a third of this quantity is actually needed, however, to achieve optimal yields. The excessive use of nitrogen not only pollutes soils and bodies of water, it also has a negative impact on the climate as it is converted to nitrous oxide. The goal, therefore, must be to tailor fertilization to actual needs. Measurement technology from Fraunhofer IPM can help to achieve this goal.

According to data from the German Environment Agency, farming is responsible for some 80 percent of nitrous oxide emissions in Germany (2016 data). Nitrous oxide (N_2O) is primarily formed in wet soils that have been excessively fertilized with nitrogen, usually resulting from the microbial degradation of nitrogen compounds. These processes already occur under natural conditions. However, they are greatly exacerbated by the additional nitrogen resulting from agriculture (liquid manure), industry and transportation.

Needs-based nitrogen fertilization

The problem is anything but new, and yet the emissions of nitrous oxide from agricultural land have not decreased in around 30 years. Numerous studies provide evidence of the direct correlation between the use of nitrogen fertilizers and nitrous oxide emissions. According to our current understanding, around a third of the climate-damaging nitrous oxide emissions can be traced back to the use of nitrogen fertilizers. Using such fertilizers sparingly and efficiently therefore not only makes economic sense, it also has several important effects on the environment: Contamination of soils and ground water from leaching is minimized, the habitats of many plant and animal species are preserved, and climate protection also benefits from sparing use of nitrogen fertilizers, since harmful nitrous oxide emissions are reduced.

Measurement technology supports innovative farming

Instead of simply reducing quantities, several innovative approaches to making the best possible use of nitrogen fertilizers are also currently under discussion. Here are the three most important ones: Firstly, novel dually stabilized nitrogen fertilizers are said to reduce nitrous oxide emissions in conventional spreading. Secondly, innovative incorporation techniques should be used to help place fertilizer at an adequate soil depth such that contact with the soil is minimized; this distribution method should eliminate volatile nitrogen loss almost entirely. Thirdly, concepts for soil use that generate and preserve humus, such as varied crop rotation, should create soils with stable nitrogen dynamics and minimal nitrogen losses.

Initial field trials of these innovative farming and fertilization practices not only show a reduction in the amount of fertilizer needed for healthy plant growth, they also reveal a positive effect on root formation and crop yield. However, it has not yet been possible to assess additional reductions in nitrous oxide emissions with sufficient precision. Measurement methods that are long established in soil science and forestry are either too expensive, too laborious, or too time-consuming to implement, meaning that modern measurements are always restricted to just a few scenarios. Existing data on nitrous oxide emissions are thus rather unreliable.

In Fraunhofer's **COGNITIVE AGRICULTURE** lighthouse project (COGNAC), eight Fraunhofer institutes are jointly conducting research on technologies that can maintain the high productivity and quality levels of conventional farming while bringing them into line with the objectives of sustainable, environmentally-friendly agriculture. Measurement data play a key role here, with the intention of making such data available as the basis of a digital ecosystem. New sensor technology for nitrous oxide detection is one of the elements being developed by Fraunhofer IPM as part of this project. The project is led by the Fraunhofer Institute for Experimental Software Engineering IESE.

Nitrous oxide sensors for ground level measurements

For over ten years, Fraunhofer IPM has been developing laser spectrometers for measuring nitrous oxide emissions – albeit chiefly for the automotive sector, since unwanted nitrous oxide is also generated in combustion engines. Building on this expertise, researchers are now developing a new type of nitrous oxide sensor as part of Fraunhofer's Cognitive Agriculture lighthouse project. The aim of developing these sensors is to enable mobile measurements of nitrous oxide concentrations at ground level and at points distributed directly across fields. A compact laser spectroscopy soil sensor that provides high-resolution results is needed for this particular application.

With this application, extremely high demands are placed on the sensitivity of the nitrous oxide sensor . This is because, in the case of ground-level nitrous oxide, relevant increases in concentration are in the order of just a few ppb per minute (ppb = parts per billion, 1×10^{-9}). The measurement methods commonly employed at present use individual containers or soil flux chambers distributed across the field to collect and accumulate gas emitted from the soil. In order to achieve measurable increases in concentration that can be analyzed, closure and collection times of up to 60 minutes are not uncommon with today's standard measurement techniques, since nitrous oxide is typically emitted from soil in quantities of less than 10 µg per square meter per hour.

The development focus for the new sensor is therefore on its ability to determine nitrous oxide emissions quickly and reliably. This is the only way to achieve the high degree of coverage required within practical measurement times. Consequently, Fraunhofer IPM is using an innovative new measurement concept employing interband cascade lasers (ICL). These allow for clear measurement of nitrous oxide in the mid-infrared range, unimpeded by cross-sensitivity with other gases, achieving a drastic reduction in measurement times while improving accuracy at the same time. For the first time, these compact, battery-operated ICL measurement systems are enabling quasi-mobile, real-time measurements of nitrous oxide, even integrated into driverless agricultural vehicles.

Fraunhofer IPM is developing a new type of nitrous oxide sensor as part of Fraunhofer's Cognitive Agriculture lighthouse project.

Dr Raimund Brunner, P +49 761 8857-310, raimund.brunner@ipm.fraunhofer.de

GROUP **THERMAL MEASUREMENT TECHNIQUES AND SYSTEMS**

Martin Jägle, P +49 761 8857-345, martin.jaegle@ipm.fraunhofer.de

This group develops thermal sensors and systems made of various materials. Flexible substrates allow very small temperature differentials to be measured using so-called calorimeter chips and a wide range of material parameters, such as thermal and electrical conductivity, to be determined using press-on measuring structures.

Group Manager: Martin Jägle

>> The "Harsh Environment Laboratory" is used to test the reliability of sensors when exposed to high temperatures and pressures.

EXPERTISE

Development and manufacture of custom-tailored microstructures and microsystems | Customer-specific measurement systems for temperature dependent determination of material parameters | Coupled thermal-electrical finite element models for thermal impedance analysis

APPLICATIONS

Low-cost fluid sensor technology on polymer substrates, e.g. for monitoring oil quality | Fouling sensors for the detection of scaling in production plants | Modelling and validation of energy storage systems for geothermal applications

SPECIFICATIONS

CUSTOM-MADE MICROSTRUCTURES

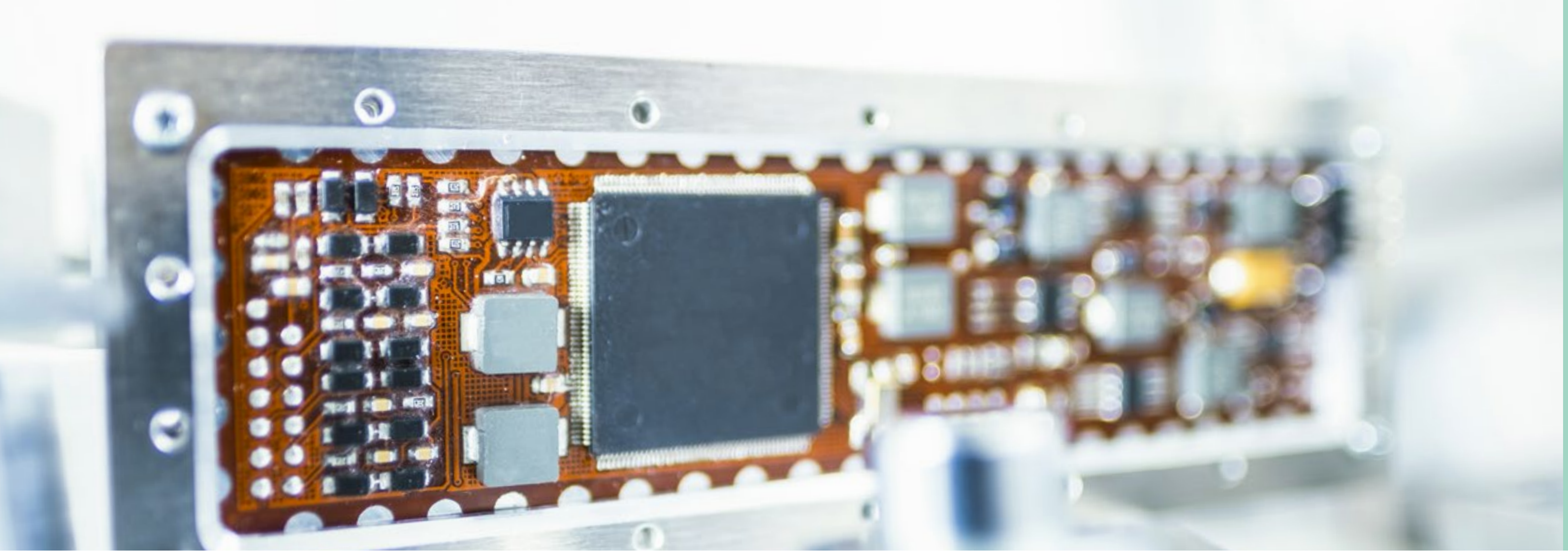
- Microstructures for organic electronics, heaters and microfluidics with structures of typically 1 µm
- Thermopile sensors, fouling sensors, calorimetric sensors
- Thermal sensors for determining material parameters, especially thermal conductivity
- Electronic tongues

THERMAL MEASUREMENT SYSTEMS

- Systems for determining electrical conductivity, charge carrier concentration, Seebeck coefficient, majority charge carriers, e.g. by way of Hall measurements on semiconductors from –200 to 800 °C
- Systems for measurement of thermal properties of solids, liquids and gases by employing methods such as impedance and 3 omega

SIMULATION OF PHYSICAL PROCESSES

- Coupled finite element models (FEM)
- Computational fluid dynamics (CFD) with thermal analysis
- Simulation of geothermal processes and design of energy storage devices
- Thermal management for systems validation



< Highly integrated sensor systems for industry must be able to withstand extremely harsh environmental conditions.

GROUP **THERMAL MEASUREMENT TECHNIQUES AND SYSTEMS**

HE Lab: Exposing sensors to thermal and compressive stress

In many areas of life, Highly Integrated Sensor Systems are state of the art technology. However, this is not the case in industrial environments. Here, extreme temperatures and pressures, chemically aggressive or wet media, and mechanical stress often cause sensitive sensors and electronic components to malfunction. Fraunhofer IPM is using specially developed measurement technology that mimics these extreme conditions in order to develop particularly robust sensors.

Geothermal drilling is well underway, the turbine is spinning at full speed and: A measurement platform assumes central control of various sensors to collect digital measurement data which are then processed and "reported" to external systems. These systems utilize the data for monitoring and intelligent process control, for example by triggering an actuator. This is the vision of scientists working on the eHarsh Fraunhofer lighthouse project involving Fraunhofer IPM and other Fraunhofer institutes. Taking engine or turbine monitoring and geothermal drilling as examples of use, they are developing a model sensor platform intended to withstand extremely harsh environmental conditions. The centrally installed high-temperature and high-pressure electronics have enough processing power to read and pre-evaluate signals directly in the sensor and transferred them to a control station. Consequently, cabling for the sensors is minimized. Given the harsh operating environments, cables often prove to be a weak point – partly owing to the prevailing high temperatures and also due to poor signal transmission and the sheer quantity of cables that would be necessary to operate a sensor network.

HE Lab — customized materials testing

High-performance sensors and electronics components that can withstand temperatures of up to 300 °C and pressures of up to 1000 bar are the building blocks of these systems. Since such sensors and components are not yet commercially available, specialized measurement technology is needed to develop and characterize them. The team therefore constructed a measurement laboratory that can replicate the actual environmental conditions as closely as possible. The HE Lab (Harsh Environment Laboratory) is used to test components and systems exposed to high temperatures and pressures. The first test rig for electronic components was put into operation in early 2019; customized measuring stations for small electronic components and for systems with volumes of up to several liters will likely be available in the new institute building from 2020 onward. The measuring range covers temperatures of up to 200 °C and pressures of up to 2000 bar. Installations for pressure shock and vibration testing are also being planned.

In addition to stress testing in the HE Lab, a high-temperature measurement platform for controlling sensors is also being constructed inside the measurement chamber.

IMPEDANCE ANALYSIS In electrical engineering, impedance is the frequency-dependent, complex resistance of a component. It is made up of ohmic, capacitive and inductive parts. Impedance measurements provide a wide range of information: Conventional conductivity can be measured at low frequencies while high-frequency measurements provide additional insights into dielectric properties — in other words, the capacitance of the measured object. When supplemented by frequency-dependent measurements of thermal properties, further information can be gained as to the object's thermal conductivity and capacitance.

It contains a control unit and various interfaces for connection to integrated and external sensor components. The components employed are all commercially available, though the permitted operating temperatures only range from 150 °C to 210 °C. Initial temperature tests on these electronics at 210 °C were successful. Many of the components used have already withstood pressure testing at up to 2000 bar, though a pressure-resistant, hermetically sealed housing is still needed for continuous operation in the field.

Impedance analysis yields wide-ranging information

Alongside the central control unit, the team is also developing sensors which operate in these harsh conditions and supply important information, for example on surrounding media. In the case of geothermal drilling, such media may be the lubricating fluid or the wall being drilled into, though they can also be sensitive layers that provide additional information on the type of mineralization or hydrocarbon concentrations, for instance. A combination of electrical, thermal and mechanical impedance analysis represents a key technology here. Electrical impedance analysis provides insights into the conductivity of the environment; thermal impedance analysis aids in the metrological separation of different media, such as water, oil and gas. Mechanical impedance analysis, on the other hand, measures pressure, vibrations and the solidity of materials or objects in the vicinity of the sensor. This combination allows the integrated measurement system to register a wide range of information that can make the construction and operation of systems cheaper and safer.

The "Harsh Environment Laboratory" measuring range covers temperatures of up to 200 °C and pressures of up to 2000 bar.

Martin Jägle, P +49 761 8857-345, martin.jaegle@ipm.fraunhofer.de

GROUP **NONLINEAR OPTICS AND QUANTUM SENSING**

Dr Frank Kühnemann, P +49 761 8857 - 457, frank.kuehnemann@ipm.fraunhofer.de

The group's key research areas are nonlinear frequency conversion and quantum sensor technology. The team develops innovative laser light sources that operate on the basis of frequency doubling, sum-frequency generation and optical parametric oscillation. This work results, for example, in light sources that are tunable over long wavelength ranges, or sum-frequency converters that transfer radiation from the mid-wave infrared range into visible light. Such light sources broaden the horizons of measurement technology, for example in gas spectroscopy, materials characterization and holography applications. The researchers are able to draw on extensive experience with optical materials, such as lithium niobate. The focus of their quantum sensor technology research is on evaluating new measurement techniques that are based on the use of specially prepared photon states.

Group Manager: Dr Frank Kühnemann

>> As part of the Fraunhofer-Max-Planck Cooperation Program (COSPA project), Fraunhofer IPM wants to make frequency comb technology usable for broadband molecular spectroscopy in real-time process analysis.

EXPERTISE

Nonlinear optical frequency conversion for generating tunable laser light and for IR detection | Development of new methods for laser-based photothermal absorption spectroscopy | Nonlinear interferometry

APPLICATIONS

Fast IR emissions spectroscopy for the analysis combustion processes | Tunable laser sources for science and industry, e.g. for holography applications | Materials characterization for high-power lasers

SPECIFICATIONS

NONLINEAR OPTICS

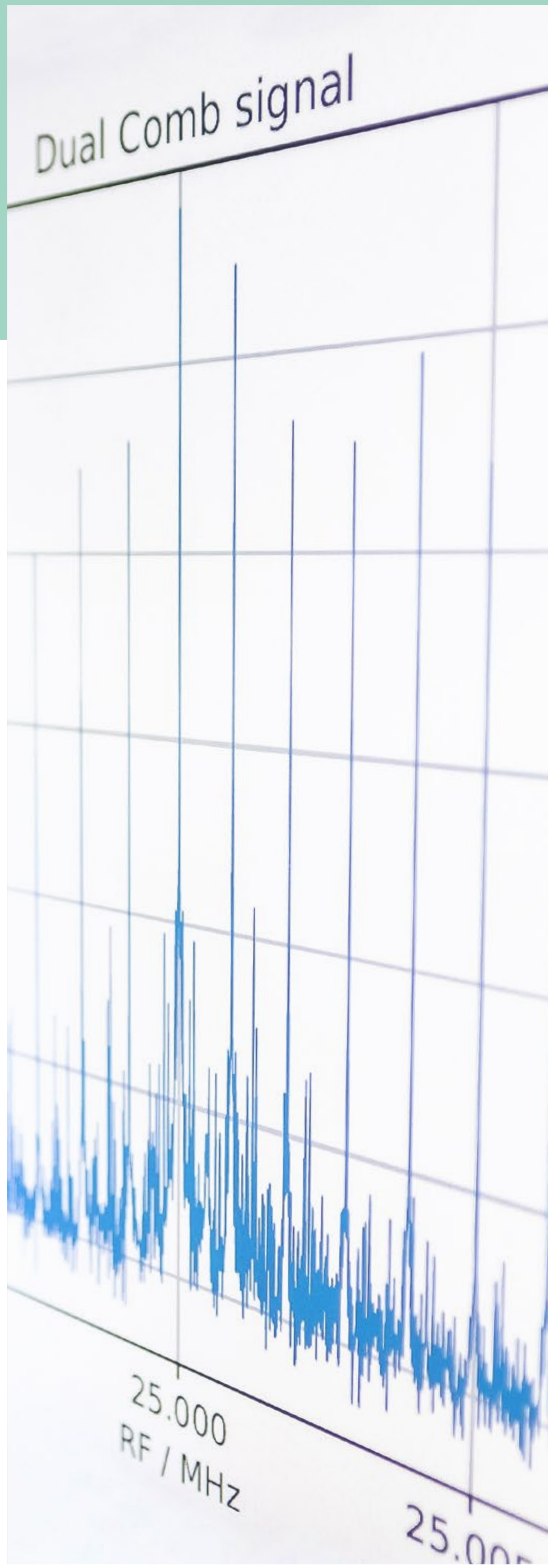
- Optical parametric oscillators – tunable from 450 nm to 5 µm with a power output of 10 mW to 2 W (wavelength-dependent) and a linewidth of 1 MHz
- Frequency doubling – conversion efficiency of over 50 percent
- MIR-NIR conversion – MIR process data recorded at more than 5000 spectra per second

LASER ABSORPTION SPECTROSCOPY

- Photothermal techniques for highly sensitive absorption spectroscopy in solids and gases
- Measurement of spectra in visible, near and mid-wave infrared ranges
- Determining residual absorption in materials down to 1 ppm

QUANTUM SENSOR TECHNOLOGY

- Nonlinear interferometry for the wavelength range from 1 to 4 µm
- Acquisition of spectral information in wavelength ranges difficult to access
- Infrared spectroscopy analytics with "undetected photons"



< This false-color image depicts an interferogram in the visible spectrum taken by a CMOS camera. It contains spectroscopic information from the mid-wave infrared range which was translated into a visible image using correlated photon pairs.

GROUP **NONLINEAR OPTICS AND QUANTUM SENSING**

Quantum sensors: Measuring with entangled photons

Effects seen in the quantum world open up surprising opportunities for measurement technology, too. The properties of entangled photons can be used in spectroscopy, for instance, to gather valuable spectral information from wavelength ranges which are otherwise difficult to access. Fraunhofer IPM is working together with other Fraunhofer institutes on the continued development of cutting-edge quantum sensor-based measurement technology targeted at potential industrial application.

Research in quantum mechanics has resulted in a series of scientific breakthroughs in the past years. In science, politics and industry, this is known as the second quantum revolution, in which quantum technology is emerging as a key technology in our modern information society. Unlike with the first generation of quantum technologies, which was based on the use of large ensembles, individual quantum systems can now be prepared, manipulated, transmitted and measured in their entanglement and in superposed states.

Quantum sensor technology – new measuring potential
Quantum sensor technology refers to sensor technology which is capable of measuring physical parameters by exploiting the specific properties of isolated quantum systems. This can involve atoms in specially prepared electronic states, localized states in solids, or photons whose properties are "entangled." On account of the methods they employ, quantum sensors and the measurement systems based on them are often more complicated in their construction than traditional sensors. But they do have significant advantages in terms of sensitivity and measuring accuracy, the best-known example being the development of atomic clocks using ultracold atoms.

Entangled photons enable the development of new measurement technologies for imaging and spectroscopy. To make this happen, a nonlinear optical medium – a crystal with special physical properties – is excited by suitable laser light, causing single photons from the laser beam to be converted in a parametric process into correlated pairs consisting of two entangled photons. Each pair of entangled photons can be seen as a singular quantum system. Thus, their properties are extremely closely correlated. This means that measuring a property of one photon in the pair gives a direct indication of the corresponding property of its partner photon.

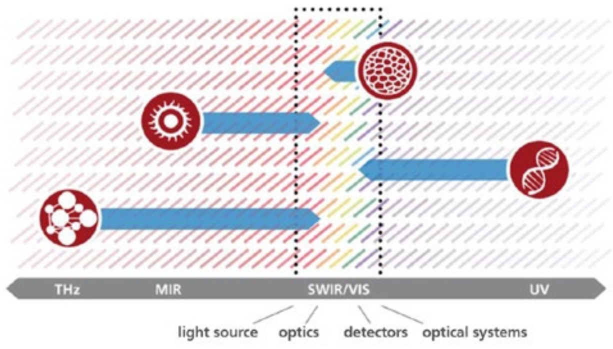
Particularly interesting for spectroscopy is the possibility of creating these entangled photon pairs with different wavelengths, allowing us to obtain valuable spectral information from difficult-to-access wavelength ranges. The key is that, with this method, the spectral information is carried not just by the photon which interacts with the sample, but also by the correlated partner photon.

The goal of Fraunhofer's **"QUANTUM METHODS FOR ADVANCED IMAGING SOLUTIONS" (QUILT)** lighthouse project is to implement the findings of quantum technology research in innovative components and systems as well as in functional demonstrations. QUILT is focused on the field of quantum imaging, where non-classical states of light are used to implement new imaging and spectroscopy methods. The project is coordinated jointly by Fraunhofer IOF and Fraunhofer IPM. Four other Fraunhofer institutes belong to the consortium. The project has been ongoing since September 1, 2017, and is set to be completed by August 31, 2020.

MIR spectroscopy with entangled photons
The mid-wave infrared (MIR) range is often described as the fingerprint region, since many materials can be particularly well detected and differentiated in this wavelength range between approximately three and 15 micrometers, where they exhibit characteristic absorption bands. Yet there is one problem – this spectrum requires sophisticated lasers, and suitable detectors for the MIR range are technically complex and expensive.

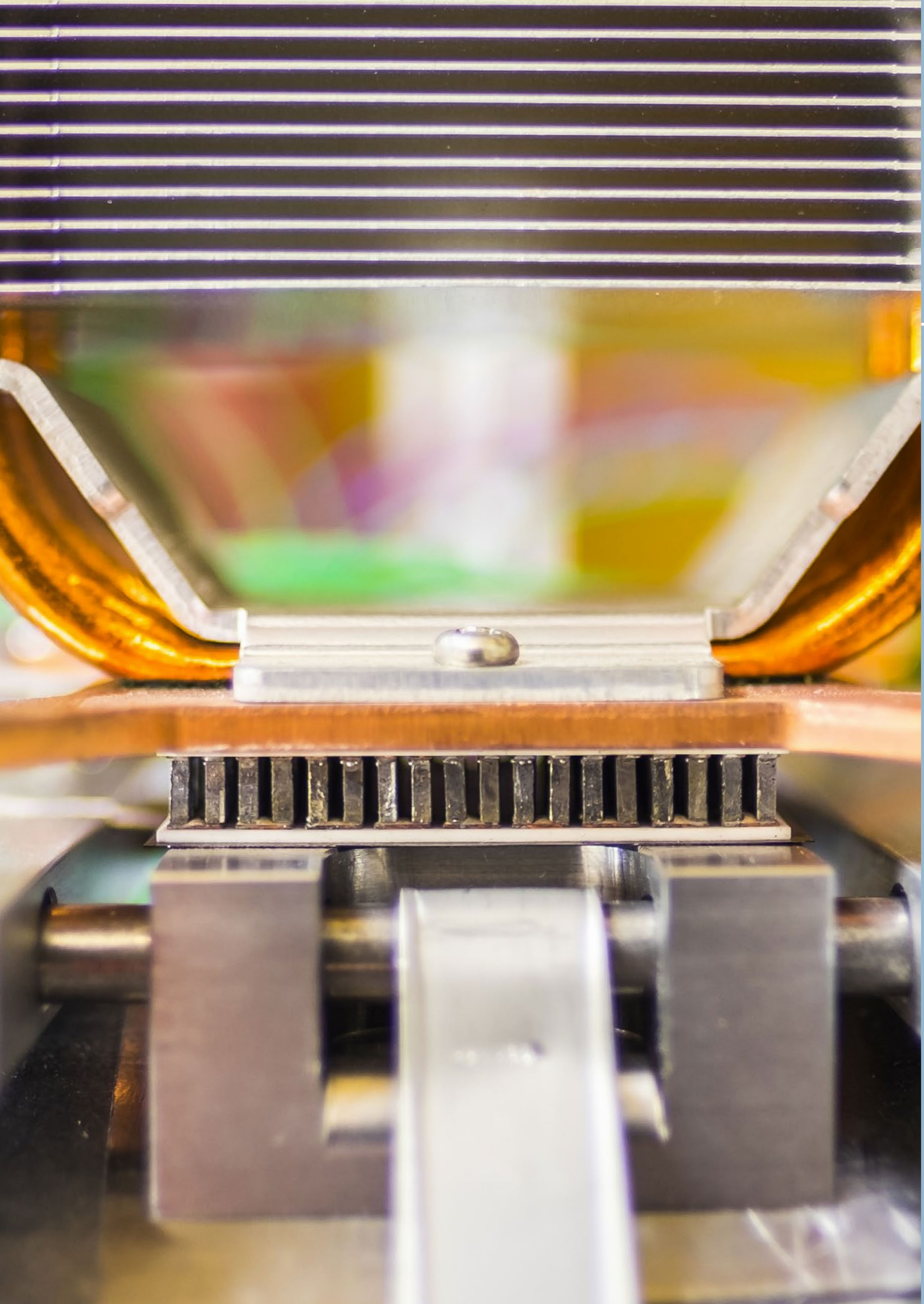
So the team at Fraunhofer IPM relies on an alternative approach in which the photon pairs each comprise one visible photon and one mid-wave infrared photon. The infrared photons interact with the sample to be examined. The visible partner photons then make it much quicker and easier to access spectroscopic information in greater detail with measurement techniques using standard detectors or cameras.

A novel field of work with great potential
Contrary to other areas of quantum sensor technology, the use of such spectrally widespread photon pairs for spectroscopy is still a new field of work. Fraunhofer IPM is actively involved in an early phase of research aimed at using its own work to explore this technique's potential for possible spectroscopic and analytical applications and later harnessing it for industrial solutions. This work is part of Fraunhofer's QUILT lighthouse project.



Correlated pairs of photons with a broad spectrum of wavelengths allow for easier detection of spectral information in the ultraviolet (UV), mid-infrared (MIR) and terahertz (THz) ranges. Silicon detectors gather the spectroscopic information by measuring a correlated photon in the visible spectral range (SWIR/VIS).

Dr Frank Kühnemann, P +49 761 8857-457, frank.kuehnemann@ipm.fraunhofer.de



BUSINESS UNIT **THERMAL ENERGY CONVERTERS**

"We are working on next generation cooling technologies."

Functional materials with special physical properties are a focus of the research performed by the "Thermal Energy Converters" business unit. We use caloric and thermoelectric materials to build innovative systems for cooling, temperature control and converting heat into electricity.

Using these materials in heat pumps, cooling systems and generators makes the systems we develop especially environmentally friendly, cost-efficient and durable. Beyond that, we devise, build and characterize new types of heat pipes.

Group **Thermoelectric Systems**

- Waste heat recovery (electric output in the kilowatt range)
- Energy self-sufficient furnaces (electric output in the watt range)
- Energy harvesting (electric output in the milliwatt range)
- Peltier cooling

Group **Caloric Systems**

- Efficient cooling and heating (magnetocalorics, elastocalorics, electrocalorics)
- Efficient heat transfer by means of latent heat (heat pipes)
- Thermal management

CONTACT

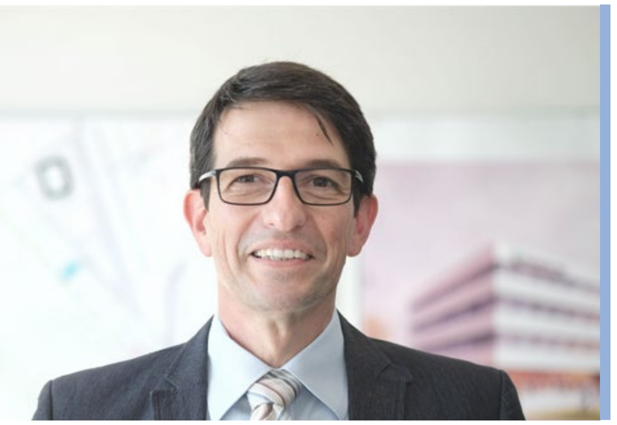
Dr Olaf Schäfer-Welsen
Head of Department
P +49 761 8857 - 173
olaf.schaefer-welsen@
ipm.fraunhofer.de

< Excellent thermal contacting is crucial for the efficiency of a thermoelectric generator.

GROUP **THERMOELECTRIC SYSTEMS**

Dr Olaf Schäfer-Welsen, P +49 761 8857 - 173, olaf.schaefer-welsen@ipm.fraunhofer.de

The group's primary focus is the development of thermoelectric modules and systems for converting thermal energy into electricity. Thermoelectric modules developed by the group are used for waste heat power generation in high-temperature processes as well as for energy harvesting, i.e. the use of very small temperature gradients. In a reverse process, the can be used for cooling (Peltier cooling). Our work draws on more than 20 years of experience in material and module development, far-reaching expertise in measurement techniques, simulation and system integration. A core competence in this context is the development electrical and thermal contacts with high temperature stability.



Group Manager: Dr Olaf Schäfer-Welsen

>> Thermoelectric generators can supply a pellet stove with electricity for control engineering and smart home applications.

EXPERTISE

Cost-efficient, semi-automatic fabrication of thermoelectric modules using positioning robots | System engineering for demonstrators and functional field tests or tests on in-house test stands | Simulation and validation measurements for an optimal design of thermoelectric modules

APPLICATIONS

Thermoelectric generators for enhancing electrical efficiency of combined heat and power plants (CHPP) | Thermoelectric generators for energy self-sufficient, low-emission furnaces | Thermoelectric generators for converting very small amounts of energy into electricity for the measurement and transmission of relevant information | Thermoelectric generators for cooling and precise temperature control in a wide range of applications

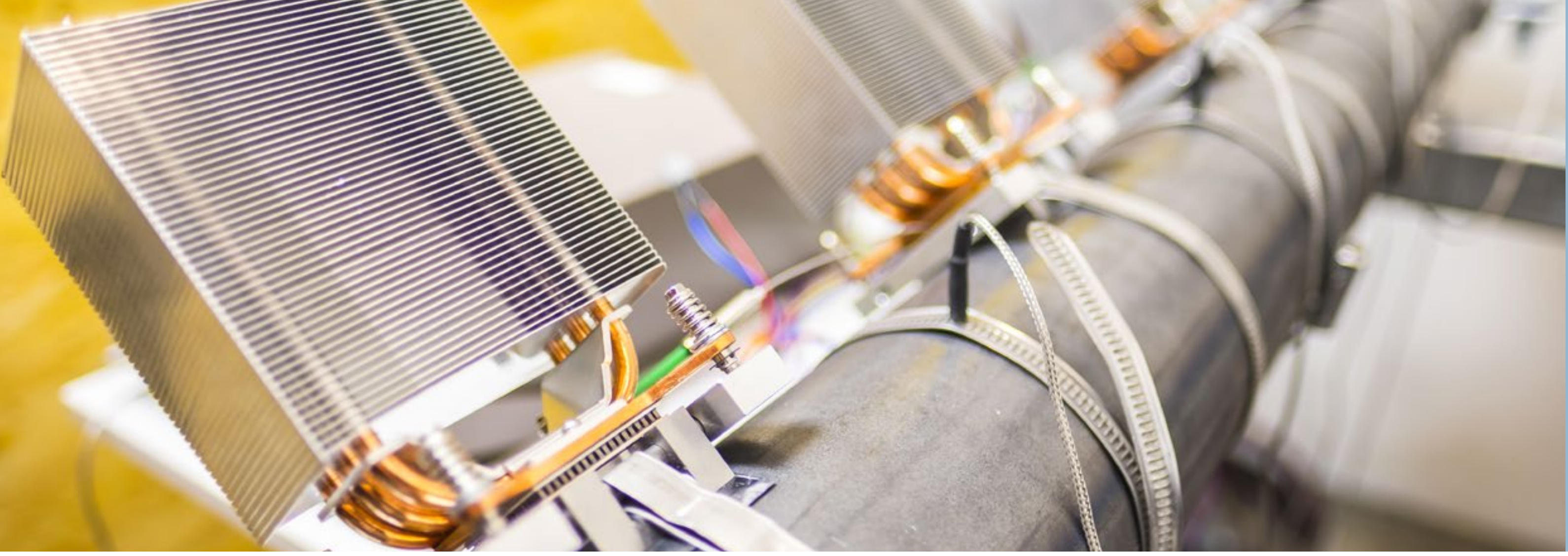
SPECIFICATIONS

WASTE HEAT RECOVERY
- Thermoelectric modules for high-temperature applications
- Enhancing electrical efficiency of CHPP with the help of thermoelectric modules
- Turning waste heat into electrical energy: in cars and in industrial processes

ENERGY SELF-SUFFICIENT FURNACES
- Thermoelectric modules for low electric output
- Energy self-sufficient operation of electric system components
- Energy self-sufficient measuring and control technology

ENERGY HARVESTING
- Converting waste heat into smallest electric output
- Power management
- Data transmission and analysis
- Comprehensive solutions suitable for IoT applications

PELTIER COOLING
- Precise temperate control of processes and components
- Materials optimized for use at specific temperatures
- Systems for customer specific applications



< Self-powered solutions are in demand to meet the energy requirements of the many billions of sensors that make up the Internet of Things. Thermoelectric generators offer up a promising option.

GROUP **THERMOELECTRIC SYSTEMS**

Thermoelectric generators: Mini power plants for the IoT

Thermoelectric generators provide electrical energy from minuscule temperature differences. This makes them perfect for establishing a decentralized supply of small quantities of electrical power – enough to wirelessly operate sensors and transfer data in the Internet of Things (IoT). Fraunhofer IPM is developing both individual thermoelectric components and complete platforms for use in sensor networks.

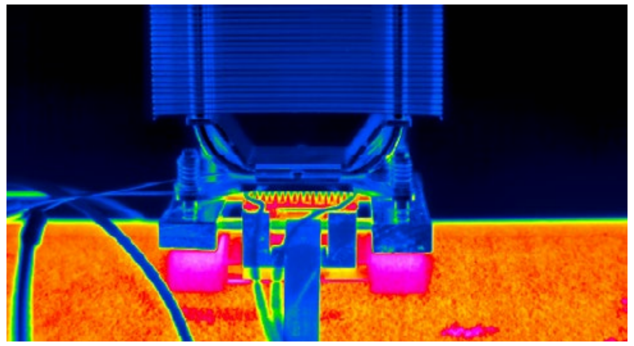
The world is becoming more interconnected than ever. This is true of people, of course, communicating with other people over the internet – but also, increasingly, of objects. The IoT has been evolving rapidly over the last few years. Billions of devices and systems are already connected, with more being added every day. The IoT communicates not with words, but with sensor data. Sensors are being installed in more and more places. This makes it possible to continuously monitor and control devices, systems, processes and infrastructure. There are already countless practical applications, from smart homes to smart lighting to smart roads. Interconnected production has become a major trend in the industrial sector, too. While some applications focus on saving energy, research and development is turning its attention to the energy consumption of these ever higher-performing interconnected sensors, generating demand for new concepts for energy-efficient, self-powered sensors and data management strategies. And the current trend is toward decentralization, with the aims being local energy provision and decentralized data evaluation.

First mover: Aircraft
One way to create an energy supply for self-powered sensors is by using thermoelectric generators (TEGs). These obtain small quantities of electricity from temperature differences or changes in temperature over time. The electricity can then be used to supply sensors without the need for batteries or maintenance. This process, described as energy harvesting, promises to be particularly useful in aviation. Wireless operation is advantageous for aircrafts, because cables increase fuel demand – due to their added weight – and system complexity. Fraunhofer IPM has carried out a number of projects over the last decade focused on developing self-powered sensors for the aviation sector, where they are most commonly used for structural health monitoring and predictive maintenance. The sensors can be installed on the airplane's fuselage, for example, to monitor mechanical loads during operation, in turn enabling early detection of any material wear and tear.
In a project which ran until the end of 2017, Fraunhofer IPM refined this technology for use with carbon fiber reinforced plastics (CFRPs) and developed an accompanying test environment for simulating flight temperature profiles. The thermoelectric mini power plants draw their energy either from the temperature difference between the airplane's interior and exterior fuselage, or from the temperature change on takeoff and landing. At stationary temperature differences of approximately 40 K, the TEG generates electrical power amounting to about 1 milliwatt per 10 grams.

THERMOELECTRIC GENERATORS (TEG) convert heat flow into electrical power. This works thanks to the Seebeck effect – a phenomenon in which an electrical field is created when two metallic conductors which each have a different temperature are joined. The resulting temperature gradients can be used to "harvest" electricity. Self-powered sensors only require temperature differences of 5–10 Kelvin to generate electrical power in the milliwatt range.

The concept of using changes in temperature over time, like those that regularly occur during airplane takeoff and landing, can also easily be transferred to other applications. Bridges and buildings have high thermal mass, meaning they react very slowly to changes in temperature. When temperatures fluctuate over the course of the day, these fluctuations can be used to form a local temperature gradient, which allows to operate thermoelectric sensors. Utilizing high thermal masses is not the only way to harvest energy from temperature fluctuations over time; reversible chemical processes or the phase transitions of phase-change materials (PCMs) can also be harnessed to this effect.

Edge computing – interpreting data at the point of measurement
As the IoT evolves, the focus is no longer just on ways to power sensors. Current work is increasingly exploring strategies for interpreting and transferring sensor data. If such vast numbers of sensors are to be digitally interconnected, it must be possible to reduce and pre-evaluate the data in a decentralized manner – i.e., at each individual point of measurement. This is the only way to limit the quantity of data so that it can be easily transferred via radio. Fraunhofer IPM is currently working with partners to develop a self-powered measurement platform. In addition to sensor technology and a TEG-based energy supply, the platform includes power management and radio sensor technology. It can be installed on the outer wall of a warm pipe, for example, to generate electrical energy from the temperature difference between the pipe wall and the surrounding medium. A range of parameters can be measured, including temperature, humidity or rate of flow. The measurement data are processed in situ before being transferred to a cloud service via long-range radio. The ultimate goal is to increase the energy yield from TEGs so that measurement data can be continuously collected and processed entirely at the sensor. Analytical strategies based on artificial intelligence (AI) can then be used to ensure that such systems only transfer measurement data onwards once a predefined threshold value is reached.



Self-powered pipe monitoring – the TEG installed on the warm outer wall of this pipe delivers electrical power for operating sensors, power management systems and radio sensor technology.

Dr Olaf Schäfer-Welsen, P +49 761 8857-173, olaf.schaefer-welsen@ipm.fraunhofer.de

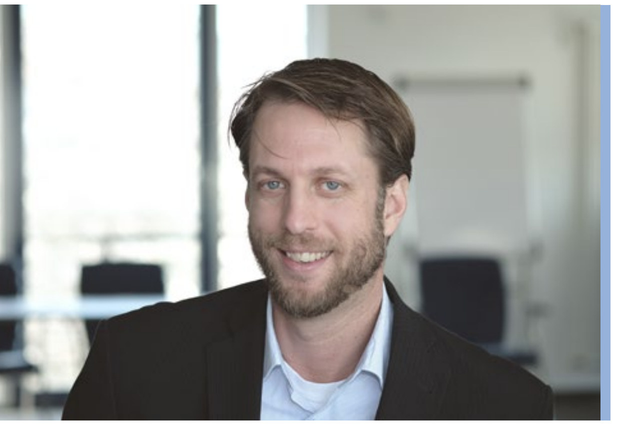
BUSINESS UNIT **THERMAL ENERGY CONVERTERS**

GROUP **CALORIC SYSTEMS**

Dr Kilian Bartholomé, P +49 761 8857 - 238, kilian.bartholome@ipm.fraunhofer.de

The group's research focuses on developing innovative systems that facilitate efficient heating and cooling using caloric materials. The goal is to make heat pumps and cooling systems exceptionally efficient and eco-friendly through the use of magnetocaloric, electrocaloric and elastocaloric materials. Our work draws on more than 20 years of experience in functional materials, in particular the characterization, simulation and system integration thereof.

In addition, the group is developing new types of heat pipes to enable efficient heat transfer in heat-stressed components. These "pulsating heat pipes" transfer heat by an order of magnitude more efficient than copper, and thus lay the foundations for an entirely new type of heat release in components exposed to extreme thermal stress.



Group Manager: Dr Kilian Bartholomé

>> Based on the magnetocaloric effect, energy efficient cooling systems can be developed, opera-ting entirely without refrigerants.

EXPERTISE

Magnetocaloric, electrocaloric and elastocaloric systems for efficient heating and cooling | Design, manufacture and characterization of pulsating heat pipes that efficiently transfer thermal energy away from hotspots

APPLICATIONS

Cooling of lab devices using caloric systems | Creating efficient heat pumps without harmful fluids to enable the heating revolution | Optimized thermal management to minimize the risk of electronic component failure

SPECIFICATIONS

EFFICIENT HEATING AND COOLING

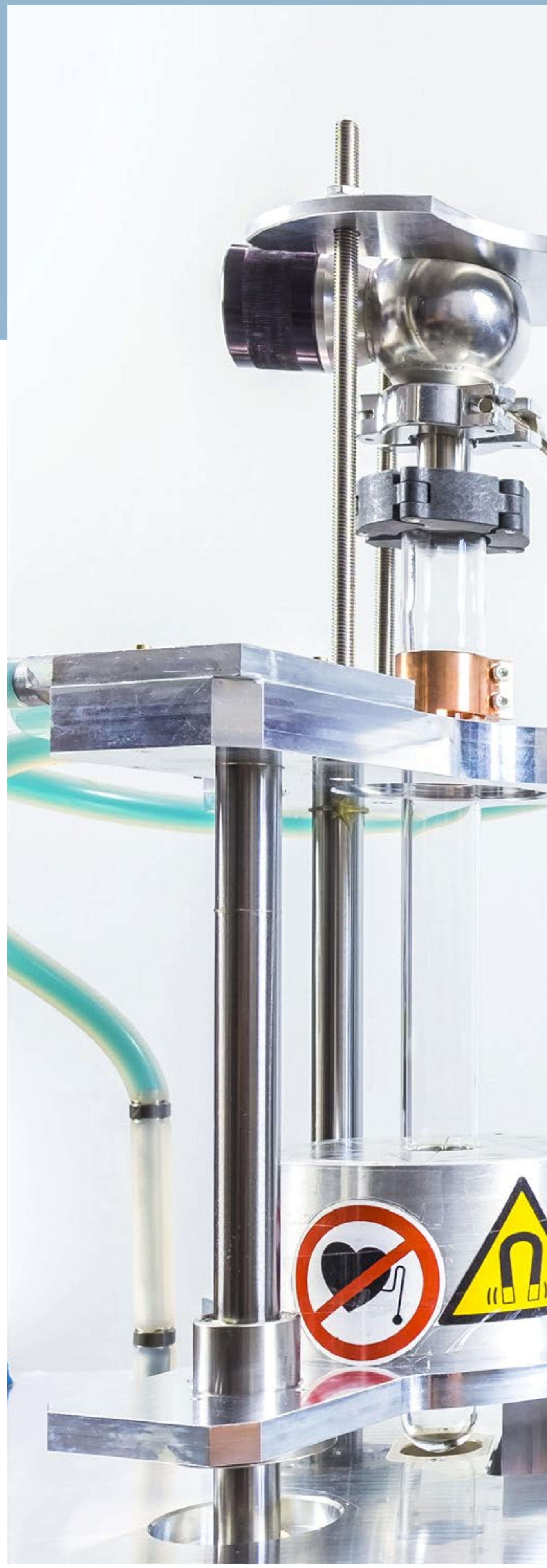
- Reduced energy needs thanks to efficient technology
- Heating and cooling without harmful refrigerants
- Compact design resulting from high energy density of caloric materials
- Low-maintenance systems

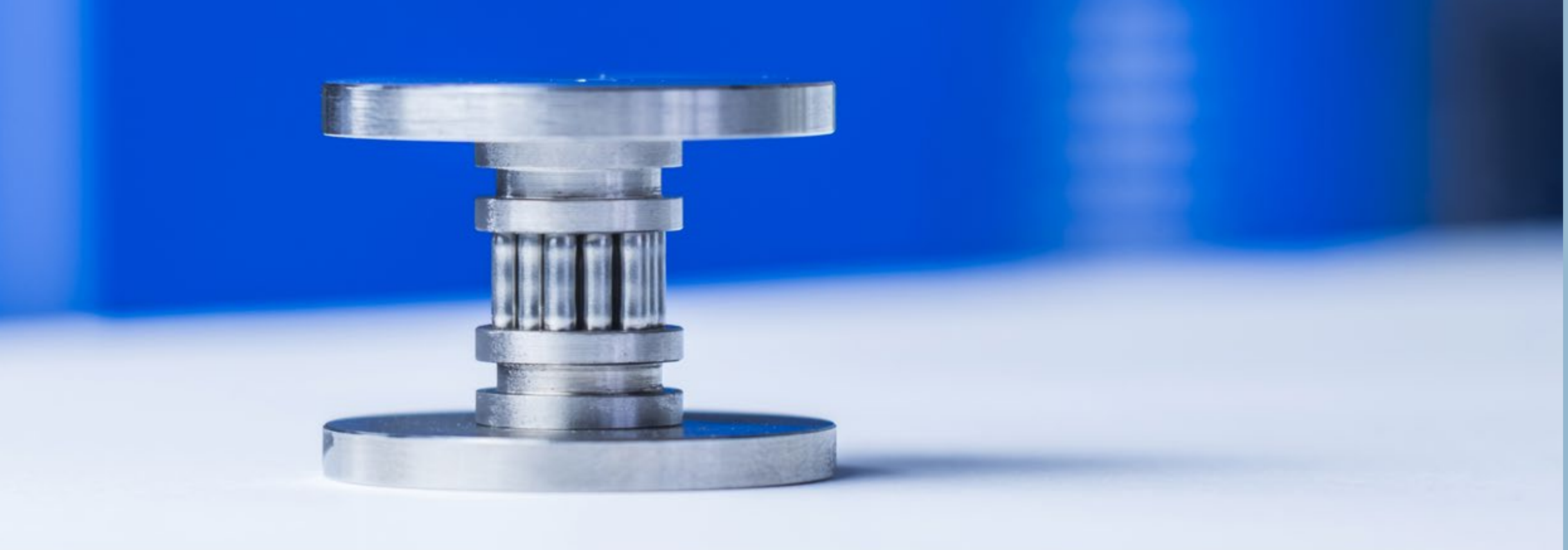
THERMAL MANAGEMENT

- Fast, precise temperature control with Peltier elements
- Passive cooling of electronic components using heat pipes
- Efficient heat distribution thanks to pulsating heat pipes
- Thermal conductance > 4000 W/m · K

HIGH EFFICIENCY HEAT TRANSFER WITH LATENT HEAT

- Heat transfer via evaporation and condensation
- High heat transfer coefficient of > 10^5 W/(m² · K)
- Extremely fast and efficient heat transfer within the system > 5 Hz





< For cooling, Fraunhofer IPM relies on pressure-based elastocaloric systems, which prove to be particularly stable in the long term.

GROUP **CALORIC SYSTEMS**

Small fridge, big potential: Cooling with elastocaloric materials

For some years now, scientists at Fraunhofer IPM have been researching solid-state cooling technologies. And their research has yielded success. At the cooling technology trade fair Chillventa 2018, the team presented the world's first mini refrigerator operated with the assistance of an elastocaloric cooling system.

Solid-state heat pumps using caloric materials may one day be able to replace the compressors commonly used in cooling technology today. This is because caloric cooling systems have two big advantages: They may be more efficient than compressors and they operate without harmful refrigerants.

The elastocaloric cooling principle

When tensile force or pressure is exerted on elastocaloric materials, a crystalline phase change takes place in which they are heated from the initial temperature T_0 to $T_0+\Delta T$. The heat generated is transferred to a heat sink and the temperature of the material returns to the temperature T_0. If the mechanical stress is removed, the material cools to a temperature below the initial level ($T_0-\Delta T$). On placing the material in contact with an object that needs to be cooled, it absorbs heat until the initial temperature is reached. By repeatedly exerting stress on the material and then releasing it, and combining this with an appropriate means of heat transfer, a cooling cycle is formed. Such an elastocaloric cooling system was constructed at Fraunhofer IPM and has now surpassed the three million cycle mark for the first time – an important step toward long-term stability and thus toward marketability. The benchmark for potential commercialization lies at around three billion cycles. When we consider the operating principle of elastocaloric systems, it is obvious why this presents something of a challenge, since the principle is almost inherently designed to suffer from material fatigue. Rapid stretching and releasing of the material causes microcracks to form, which sooner or later lead to tearing. As a consequence, elastocaloric systems that employ material stretching to induce temperature change currently only achieve some ten thousand cycles.

A new approach using compression

In view of this, Fraunhofer IPM has adopted a different approach: Instead of stretching the elastocaloric (EC) material, it is compressed using a special compression system. The system constructed at Fraunhofer IPM utilizes Nitinol rods measuring 11 mm in length and 2.5 mm in diameter. Compressing the materials is equivalent to subjecting them to tensile stress at comparable temperature differences, but without inducing cracking. Nevertheless, this approach does present significant challenges compared to the application of tensile force. When stretching elastocaloric materials, ultrafine wires – if necessary several meters in length – can be employed so that relatively low system force is needed. Such fine wires would simply buckle if compressed. As a result, the length of the rods – and thus the surface area available for heat transfer – is lower in pressure-based systems than in stretching systems.

ELASTOCALORIC (EC) MATERIALS are shape-memory alloys which revert to their original shape after being deformed, for instance as the result of stretching or compression. The commercially available nickel-titanium alloy Nitinol is one of the best-known EC materials. However, it suffers from material fatigue after just a few thousand cycles when stretched. New materials promise to push this threshold far higher in future. In 2015, a German-American research team developed an alloy ($Ti_{54}Ni_{34}Cu_{12}$) which, through the addition of copper to the conventional nickel-titatnium compound, has achieved a stability of more than 10^7 cycles.

Patented heat transfer concept

The system developed by Fraunhofer IPM offsets the low levels of heat transfer resulting from this unfavorable aspect ratio using a particularly efficient patented concept for transferring heat between the EC material and the heat exchanger unit. This heat transfer is usually achieved by actively pumping a fluid or by means of pressure contacts between the elastocaloric material and the heat exchanger. Fraunhofer IPM, however, relies on a passive approach of latent heat transfer, a concept also used in heat pipes and thermosiphons. Here, heat is transferred (latently) by evaporating and condensing a fluid – in this case water. The fluid is contained in a hermetically sealed tube that is free from all non-condensing gas, and is present in both liquid and gaseous form. Individual elastocaloric segments are connected in series and designed as thermal diodes so that heat is then transported segment by segment in a single direction, and one side of each segment is cooled while the other is heated. The heat transfer coefficient reaches values of up to 100 kW / (m²·K), and is therefore many orders of magnitude higher than that achieved using other heat transfer concepts. This approach enables cycle frequencies of over 10 Hz, which are an essential prerequisite of cost-effective, marketable systems.

The prototype for the elastocaloric mini refrigerator demonstrates that solid-state cooling concepts can achieve the long-term stability required. However, there is still much to do to make them market-ready. At present, the team is working on improvements to the system design using simulations of optimized components as well as on strategies for fully recovering the pressure energy used for compression. This will allow them to increase cooling performance and energy efficiency. In addition to elastocaloric cooling concepts, Fraunhofer IPM is also conducting successful research on magnetocaloric cooling technology. Read more about this in the interview with Dr Jochen Kopitzke from cooling technology manufacturer Philipp Kirsch GmbH (p. 22-23).

Prototype of an elastocalorically operated mini refrigerator developed at Fraunhofer IPM.

Dr Kilian Bartholomé, P +49 761 8857 - 238, kilian.bartholome@ipm.fraunhofer.de

> InnoTrans 2018: Prof Dr Alexander Reiterer (front right) talks to a client at the Fraunhofer Traffic and Transportation Alliance booth.

TRADE FAIRS 2018

Control
International Trade Fair for Quality Assurance
Stuttgart, 4/24–4/27/2018
Fraunhofer Vision Alliance booth
Fraunhofer IPM exhibited two inline techniques for measuring surface parameters: HoloCut, a digital holography measurement system that allows 3D component measurement to be performed with micrometer accuracy, and fluorescence imaging analysis systems that detect surface contamination and defects.

LaSyS
International Trade Fair for Laser Material Processing
Stuttgart, 6/5–6/7/2018
Fraunhofer IPM presented the HoloCut 3D inline measurement system as a co-exhibitor at the Baden-Württemberg Stiftung gGmbH booth. In this system, the digital holography sensor maps the topography of component surfaces directly in the machine tool.

ACHEMA
World Forum and Leading Show for the Process Industries
Frankfurt, 6/11–6/15/2018
Own booth
The Gas and Process Technology department exhibited systems for analyzing complex gas mixtures as well as for the inline analysis of liquids. In addition, the institute presented a variety of sensors and sensor concepts for gas and liquid measurement, as well as light sources for spectroscopy.

SENSOR+TEST
The Measurement Fair
Nuremberg, 6/26–6/28/2018
Joint Fraunhofer booth
The Integrated Sensor Systems and Thermal Measurement Techniques and Systems groups presented a wide range of sensors and sensor systems for immissions and emissions monitoring, food quality control, industrial process monitoring, and liquid analytics. Prof Dr Jürgen Wöllenstein led the two-day "19th ITG/GMA Symposium on Sensors and Measurement Systems 2019", which ran in parallel to the trade fair.

InnoTrans
Leading International Trade Fair for Transport Technology, Innovative Components, Vehicles and Systems
Berlin, 9/18–9/21/2018
Fraunhofer Traffic and Transportation Alliance booth
Fraunhofer IPM exhibited at InnoTrans 2018 with offerings in the areas of clearance measurement, automated interpretation of 3D measurement data, and UAV-based laser scanning.

Chillventa
The Exhibition for Energy Efficiency, Heat Pumps and Refrigeration
Nuremberg, 10/16–10/18/2018
Own booth
At the international Exhibition for Energy Efficiency, Heat Pumps, and Refrigeration, colleagues in the Thermal Energy Systems department presented magnetocaloric and elastocaloric cooling systems that use heat pipes to facilitate efficient heat transfer. Concepts and technologies for cooling and temperature control – including pulsating heat pipes – were also on display.

INTERGEO
Conference and Trade Fair for Geodesy, Geoinformation and Land Management
Frankfurt, 10/16–10/18/2018
Own booth
The institute presented laser scanners and camera systems for mapping structures with large surface areas in 3D. Exhibits included a clearance profile scanner that surveys transport routes from vehicles and trains. The Lightweight Airborne Profiler, a combined laser scanner and camera system that was developed for performing 3D measurements from aerial vehicles (UAV), was also presented for the first time. A deep learning framework for the automated interpretation of 3D measurement data was likewise featured at the trade fair.

parts2clean
Leading International Trade Fair for Industrial Parts and Surface Cleaning
Stuttgart, 10/23–10/25/2018
Fraunhofer Cleaning Technology Alliance booth
Fraunhofer IPM exhibited the F-Scanner used for performing surface inspections. The scanner employs fluorescence measurement technology to provide imaging measurements of oil coatings or to check for surface contamination. In addition, for the first time, the institute exhibited a measurement system that provides imaging detection of particulate impurities on surfaces. This was the inline particle detector, which works with a combination of different imaging techniques. Andreas Hoffmann from Fraunhofer IPM also gave a forum lecture entitled "Detection and classification of filmic and particle contamination using imaging techniques".

euroBlech
International Sheet Metal Working Technology Exhibition
Hannover, 10/23–10/26/2018
Joint Fraunhofer booth
Fraunhofer IPM presented the ANALIZEsingle and ANALIZEmulti systems for layer thickness measurement and element analysis, as well as the F-Scanner for imaging measurement of oil coatings.

FAIRS 2019: PREVIEW

HANNOVER MESSE
Hannover, 04/01–04/05/2019

4. VDI-Fachkonferenz Schwingungen in Werkzeug- und Verarbeitungsmaschinen
Stuttgart, 03/26–03/27/2019

AUTOMOTIVE ENGINEERING EXPO
Nuremberg, 06/04–06/05/2019

Control
Stuttgart, 05/07–05/10/2019

LASER World of PHOTONICS
Munich, 06/24–06/27/2019

SENSOR+TEST
Nuremberg, 06/25–06/27/2019

INTERGEO
Stuttgart, 09/17–09/19/2019

parts2clean
Stuttgart, 10/22–10/24/2019

BlechEXPO
Stuttgart, 11/05–11/08/2019

< Together, Freiburg's five Fraunhofer institutes attended two regional events in 2018 to recruit qualified young people for an apprenticeship at Fraunhofer.

EVENTS AT FREIBURG'S FRAUNHOFER INSTITUTES

Job-Start-Börse Freiburg

Freiburg, 5/16–5/17/2018

Fraunhofer IPM took part in this regional trainee recruitment fair for the first time together with all four other Freiburg-based Fraunhofer institutes.

Marktplatz: Arbeit Südbaden

Freiburg, 11/16–11/17/2018

All five of Freiburg's Fraunhofer institutes were represented for the first time at the vocational training fair "marktplatz: ARBEIT SÜDBADEN 2018", where they had a joint booth. Training colleagues were on hand to answer any questions relating to apprenticeships at Fraunhofer, whilst Fraunhofer's own apprentices presented a sample of projects and provided first-hand information.

WORKSHOPS AT FRAUNHOFER IPM

Industry Workshop on Optical Gear Measurement

Fraunhofer IPM, Freiburg, 6/14/2018

Measurement technology experts from Fraunhofer IPM and Alicona Imaging GmbH, as well as invited speakers, gave an overview of current technology as well as the latest trends and developments in gear metrology. (read more on page 18)

MoLaS – Mobile Laser Scanning Technology Workshop

Fraunhofer IPM, Freiburg, 11/14–11/15/2018

For the third time the team around Prof. Dr Alexander Reiterer organized the technology workshop on mobile laser scanning. (read more on page 19)

WORKSHOPS IN 2019

Industry Workshop on Thermoelectrics

Fraunhofer IPM, Freiburg, 3/20–3/21/2019

Fraunhofer IPM is organizing the first Industry Workshop on Thermoelectrics for scientists and users of the technology.

Caloric Systems Workshop 2019

Fraunhofer IPM, Freiburg, 3/27–3/28/2019

The workshop provides experts from science and industry with an opportunity to gain and share information on the latest trends and developments in the field of magnetocaloric, electrocaloric, and elastocaloric systems.

8th Gas Sensor Workshop 2019

Fraunhofer IPM, Freiburg, 10/24/2019

The gas sensor community will meet to present and discuss technologies and applications in the gas sensor field.

OUR PARTNERS

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

Fraunhofer-Gesellschaft

- Fraunhofer-Verbund Light & Surfaces
- Fraunhofer-Allianz Food Chain Management
- Fraunhofer-Allianz Reinigungstechnik
- Fraunhofer-Allianz Verkehr
- Fraunhofer-Allianz Vision

International

- ETS – European Thermoelectric Society
- ITS – International Thermoelectric Society
- MRS – Material Research Society
- OSA – The Optical Society

Germany

- AMA Fachverband für Sensorik
- Arbeitskreis 4.3.2 Ebenheit der Forschungsgesellschaft für Straßen- und Verkehrswesen e. V. (FGSV)
- Arbeitskreis Prozessanalytik der GDCh und DECHEMA
- Competence Center for Applied Security e.V. (CAST)
- Cluster Bahntechnik e.V. (CNA)
- Deutsche Forschungsgesellschaft für Oberflächenbehandlung (DFO)
- Deutsche Gesellschaft für Photogrammetrie, Fernerkundung und Geoinformation e.V. (DGPF)
- Deutsche Hydrographische Gesellschaft e.V. (DHyG)
- Deutscher Kälte- und Klimatechnischer Verein e.V. (DKV)
- Draht-Welt Südwestfalen – netzwerkdraht e.V.
- Deutsche Thermoelektrik Gesellschaft e.V. (DTG)
- Forum Angewandte Informatik und Mikrosystemtechnik e.V. (FAIM)
- Gesellschaft Deutscher Chemiker (GDCh)
- Green City Freiburg Regional Cluster
- Innovations- und Effizienzcluster (innoEFF)
- Klimaschutz am Oberrhein e.V. (Strategische Partner)
- microTEC Südwest e.V.
- Nano-Zentrum Euregio Bodensee e.V.
- Photonics BW Innovationsnetz für Optische Technologien
- VDI/VDE – GMA Gesellschaft für Mess- und Automatisierungstechnik
- Verband für Sicherheit, Gesundheit und Umweltschutz bei der Arbeit e.V. (VDSI)

PUBLICATIONS 2018

Sandfort, V.; Goldschmidt, J.; Wöllenstein, J.; Palzer, S.
Cavity-enhanced Raman spectroscopy for food chain management
Sensors 18, 709 (2018)

Engel, L.; Tarantik, K.; Pannek, C.; Wöllenstein, J.
Colorimetric detection of hydrogen sulfide in ambient air
Proceedings. MDPI Open Access Journal 2, 804 (2018)

Schmitt, K.; Tarantik, K.; Pannek, C.; Wöllenstein, J.
Colorimetric materials for fire gas detection - A review
Chemosensors 6, 14 (2018)

Jia, Y.; Hanka, K.; Zawilski, K. T.; Schunemann, P. G.; Buse, K.; Breunig, I.
Continuous-wave whispering-gallery optical parametric oscillator based on $CdSiP_2$
Optics Express 26, 10833-10841 (2018)

Werner, C. S.; Sturman, B.; Podivilov, E.; Kini Manjeshwar, S.; Buse, K.; Breunig, I.
Control of mode anticrossings in whispering gallery microresonators
Optics Express 26, 762-771 (2018)

Szabados, J.; Kini Manjeshwar, S.; Breunig, I.; Buse, K.
Electro-optic tuning of potassium tantalate-niobate whispering gallery resonators
Kudryashov, A. V. (Ed.): Laser Resonators, Microresonators, and Beam Control XX. Proceedings of SPIE 10518, Paper 1051802 (2018)

Palzer, S.; Sandfort, V.; Goldschmidt, J.; Wöllenstein, J.
Enhancement techniques to improve Raman spectroscopy of gases
Reindl, L. M.: Sensoren und Messsysteme: Beiträge der 19. ITG/GMA-Fachtagung. ITG-Fachbericht 281, 308-310 (2018)

Pohle, R.; Pohl, T.; Pannek, C.; Tarantik, K.; Bauersfeld, M.-L.; Wöllenstein, J.; Raible, S.; Seiler, F.
Evaluation of a colorimetric sensor system for early fire detection
Proceedings. MDPI Open Access Journal 2, 966 (2018)

Schäfer, R.; Schmidtke, G.; Brunner, R.
Experiences with a three-current ionization chamber as primary detector standard for absolute calibration in space
Applied Optics 57, 6851-6859 (2018)

Seyler, T.; Fratz, M.; Beckmann, T.; Schiller, A.; Bertz, A.; Carl, D.
Extending the depth of field beyond geometrical imaging limitations using phase noise as a focus measure in multiwavelength digital holography
Applied Sciences 8, 1042 (2018)

Seyler, T.; Fratz, M.; Beckmann, T.; Bertz, A.; Carl, D.; Grün, V.; Börret, R.; Ströer, F.; Seewig, J.
Extensive microstructural quality control inside a machine tool using multiwavelength digital holography
Jaroszewicz, L. R. (Ed.): Speckle 2018, VII International Conference on Speckle Metrology. Proceedings of SPIE 10834, Paper 108342B (2018)

Herr, S. J.; Brasch, V.; Szabados, J.; Obrzud, E.; Jia, Y.; Lecomte, S.; Buse, K.; Breunig, I.; Herr, T.
Frequency comb up- and down-conversion in synchronously driven $\chi^{(2)}$ optical microresonators
Optics Letters 43, 5745-5748 (2018)

Scholz, L.; Ortiz Perez, A.; Bierer, B.; Wöllenstein, J.; Palzer, S.
Gas sensors for climate research
Reindl, L. M.: Sensoren und Messsysteme: Beiträge der 19. ITG/GMA-Fachtagung. ITG-Fachbericht 281, 453-456 (2018)

Pannek, C.; Tarantik, K.; Engel, L.; Vetter, T.; Wöllenstein, J.
Gasochromic detection of NO_2 on the example of the food additive E141 (ii)
Proceedings. MDPI Open Access Journal 2, 721 (2018)

Péntek, Q.; Hein, S.; Miernik, A.; Reiterer, A.
Image-based 3D surface approximation of the bladder using structure-from-motion for enhanced cystoscopy based on phantom data
Biomedizinische Technik 63, 461-466 (2018)

Boerman, J. K; van Harberden, J.-K.; Pannek, C.; Schmitt, K.; Tarantik, K.; Bauersfeld, M.-L.; Wöllenstein, J.
Improvement methods for colorimetric gas sensors for use in indoor livestock farming
Proceedings. MDPI Open Access Journal 2, 769 (2018)

Herr, S. J.; Buse, K.; Breunig, I.
Incoherently pumped lasing and self-pumped three-wave mixing in laser-active whispering-gallery resonators
Kudryashov, A. V. (Ed.): Laser Resonators, Microresonators, and Beam Control XX. Proceedings of SPIE 10518, Paper 105180U (2018)

Ortiz Perez, A.; Gao, H.; Lyu, X.; Wöllenstein, J.; Kallfaß, V.; Fonollosa, J.; Palzer, S.
Inkjet-printed, functional heterolayers of ZnO@CuO for stoma pouch monitoring
Applied Nanoscience 8, 1907-1914 (2018)

Pannek, C.; Tarantik, K.; Schmitt, K.; Wöllenstein, J.
Investigation of gasochromic rhodium complexes towards their reactivity to CO and integration into an optical gas sensor for fire gas detection
Sensors 18, 1994 (2018)

Wigger, B.; Meissner, T.; Winkler, M.; Förste, A.; Jetter, V.; Buchholz, A.; Zimmermann, A.
Label-/tag-free traceability of electronic PCB in SMD assembly based on individual inherent surface patterns
The International Journal of Advanced Manufacturing Technology 98, 3081-3090 (2018)

Reiterer, A.; Leidinger, M.
Laserscanner zur Lichtraummessung: Präzise messen, effizient auswerten
Der Eisenbahningenieur 69 (5), 44-47 (2018)

Seyler, T.; Fratz, M.; Grün, V.; Börret, R.; Ströer, F.; Seewig, J.
Messen am eingerichteten Werkstück: 3D-Inline-Messtechnik für die Werkzeugmaschine
Qualität und Zuverlässigkeit 63 (12), 52-54 (2018)

Jia, Y.; Hanka, K.; Breunig, I.; Zawilski, K. T.; Schunemann, P. G.; Buse, K.
Mid-infrared whispering gallery resonators based on non-oxide nonlinear optical crystals
Kudryashov, A. V. (Ed.): Laser Resonators, Microresonators, and Beam Control XX. Proceedings of SPIE 10518, Paper 105180X (2018)

Schiller, A.; Beckmann, T.; Fratz, M.; Bertz, A.; Carl, D.; Buse, K.
Multiwavelength digital holography: Height measurements on linearly moving and rotating objects
Jaroszewicz, L. R. (Ed.): Speckle 2018, VII International Conference on Speckle Metrology. Proceedings of SPIE 10834, Paper 108342E (2018)

Kogut, I. R.; Nichkalo, S. I.; Ohorodniichuk, V.; Dauscher, A.; Candolfi, C.; Masschelein, P.; Jacquot, A.; Lenoir, B.
Nanostructure features, phase relationships and thermoelectric properties of melt-spun and spark-plasma-sintered skutterudites
Acta Physica Polonica. A 133, 879-883 (2018)

Gao, H.; Amann, J.; Lyu, X.; Wöllenstein, J.; Palzer, S.
Novel method for thermal characterization of MEMS
Journal of Microelectromechanical Systems 27, 521-528 (2018)

Jägle, M.; Pernau, H.-F.; Pfützner, M.; Benkendorf, M.; Li, X.; Bartel, M.; Drost, S.; Wöllenstein, J.
On-chip temperature compensation for thermal impedance sensors
Proceedings. MDPI Open Access Journal 2, 1053 (2018)

Sandfort, V.; Goldschmidt, J.; Wöllenstein, J.; Palzer, S.
One quantum sensor for all gases: Cavity-enhanced Raman spectroscopy for food-chain monitoring
Razeghi, M. (Ed.): Quantum Sensing and Nano Electronics and Photonics XV. Proceedings of SPIE 10540, Paper 105400Z (2018)

Holz, P.; Brandenburg, A.
Ortsaufgelöste Messung filmischer Verunreinigungen
JOT Journal für Oberflächentechnik 58 (10), 46-49 (2018)

Knobelspies, S.; Bierer, B.; Daus, A.; Takabayashi, A.; Salvatore, G. A.; Cantarella, G.; Ortiz Perez, A.; Wöllenstein, J.; Palzer, S.; Tröster, G.
Photo-induced room-temperature gas sensing with a-IGZO based thin-film transistors fabricated on flexible plastic foil
Sensors 18, 358 (2018)

El-Safoury, M.; Weber, C.; Schmitt, K.; Pernau, H.-F.; Willing, B.; Wöllenstein, J.
Photoacoustic gas detector for the monitoring of sulfur dioxide content in ship emissions
Reindl, L. M.: Sensoren und Messsysteme: Beiträge der 19. ITG/GMA-Fachtagung. ITG-Fachbericht 281, 450-452 (2018)

Jia, Y.; Winkler, M.; Cheng, C.; Chen, F.; Kirste, L.; Cimalla, V.; Zukauskaite, A.; Szabados, J.; Breunig, I.; Buse, K.
Pulsed laser deposition of ferroelectric potassium tantalate-niobate optical waveguiding thin films
Optical Materials Express 8, 541-548 (2018)

Wolf, R.; Jia, Y.; Bonaus, S.; Werner, C. S.; Herr, S. J.; Breunig, I.; Buse, K.; Zappe, H.
Quasi-phase-matched nonlinear optical frequency conversion in on-chip whispering galleries
Optica 5, 872-875 (2018)

Herr, S. J.; Werner, C. S.; Buse, K.; Breunig, I.
Quasi-phase-matched self-pumped optical parametric oscillation in a micro-resonator
Optics Express 26, 10813-10819 (2018)

Bierer, B.; Nägele, H.-J.; Ortiz Perez, A.; Wöllenstein, J.; Kress, P.; Lemmer, A.; Palzer, S.
Real-time gas quality data for on-demand production of biogas
Chemical Engineering and Technology 41, 696-701 (2018)

Strahl, T.; Herbst, J.; Maier, E.; Rademacher, S.; Lambrecht, A.
Remote detection of leakages of non-IR-active gases by laser spectroscopy
Razeghi, M. (Ed.): Quantum Sensing and Nano Electronics and Photonics XV. Proceedings of SPIE 10540, Paper 105402K (2018)

Weber, C.; Kapp, J.; Schmitt, K.; Pernau, H.-F.; Wöllenstein, J.
Resonant photoacoustic detection of NO_2 with an LED based sensor
Proceedings. MDPI Open Access Journal 2, 1036 (2018)

El-Safoury, M.; Dufner, M.; Weber, C.; Schmitt, K.; Pernau, H.-F.; Willing, B.; Wöllenstein, J.
Resonant photoacoustic gas monitoring of combustion emissions
Proceedings. MDPI Open Access Journal 2, 962 (2018)

Wolf, R.; Breunig, I.; Zappe, H.; Buse, K.
Scattering-loss reduction of ridge waveguides by sidewall polishing
Optics Express 26, 19815-19820 (2018)

Wang, X.; Veremchuk, I. V.; Burkhardt, U.; Bobnar, M.; Böttner, H.; Kuo, C. Y.; Chen, C. T.; Chang, C. F.; Zhao, J.; Grin, Y.
Thermoelectric stability of Eu- and Na-substituted PbTe
Journal of Materials Chemistry. C 6, 9482-9493 (2018)

König, J. D.
Thermoelectrics - Next step in manufacturing
Nature Energy 3, 259-260 (2018)

Graunke, T.; Schmitt, K.; Busch, S.; Raible, S.; Wöllenstein, J.
Towards an empirical model for the prediction of the selectivity of polymer membranes
Proceedings. MDPI Open Access Journal 2, 979 (2018)

Schäfer, R.; Gottwald, A.; Richter, M.
Traceable measurements of He, Ne, Ar, Kr, and Xe photoionization cross sections in the EUV spectral range
Journal of Physics. B 51, 135004 (2018)

Wigger, B.; Meissner, T.; Förste, A.; Jetter, V.; Zimmermann, A.
Using unique surface patterns of injection moulded plastic components as an image based Physical Unclonable Function for secure component identification
Scientific Reports 8, 4738 (2018)

Breunig, I.; Hanka, K.; Jia, Y.; Zawilski, K. T.; Schunemann, P. G.; Buse, K.
Whispering gallery optical parametric oscillators for the mid-infrared spectral range
Vodopyanov, K. L. (Ed.): Nonlinear Frequency Generation and Conversion: Materials and Devices XVII. Proceedings of SPIE 10516, Paper 105160E (2018)

Ortiz Perez, A.; Bierer, B.; Scholz, L.; Wöllenstein, J.; Palzer, S.
A wireless gas sensor network to monitor indoor environmental quality in schools
Sensors 18, 4345 (2018)

GRANTED PATENTS 2018

Schmitt, K.; Pannek, C.
Gassensor und Verfahren zur Herstellung einer gassensitiven Schicht für einen opt. Gassensor
(Gas sensor and manufacturing process for a gas-sensitive layer for an optical gas sensor)
DE 10 2016 107 158 B4

DISSERTATIONS 2018

Bierer, B.
Entwurf und Aufbau eines robusten Gassensorsystems
Aachen, Shaker Verlag, 2018; [Freiburg/Brsg., Univ., Diss., 2018]

Eberhardt, A.
Filterrotationsspektrometer für die Detektion von Ethen
Aachen, Shaker Verlag, 2018; [Freiburg/Brsg., Univ., Diss., 2018]

Graunke, T.
Selektivitätssteigerung von Gassensoren durch symmetrisch dichte Polymere und aktiv beheizte Filter
Aachen, Shaker Verlag, 2018; [Freiburg/Brsg., Univ., Diss., 2018]

Sandfort, V.
Entwicklung von Methoden zur Verstärkung des Raman-Streueffektes in komplexen Gasgemischen
[Freiburg/Brsg., Univ., Diss., 2018]

Scholz, L.
Novel Concepts for Miniaturized Photoacoustic-based Gas Sensing Devices
Aachen, Shaker Verlag, 2019; [Freiburg/Brsg., Univ., Diss., 2018]

Werner, C.
Stabilisierung und Durchstimmung nichtlinear-optischer Prozesse in Lithiumniobat-Flüstergalerieresonatoren
[Freiburg/Brsg., Univ., Diss., 2018]

Wolf, R.
Frequenzkonversion mittels chipintegrierter Flüstergalerieresonatoren aus Lithiumniobat
Nordersted, BoD, 2018; [Freiburg/Brsg., Univ., Diss., 2018]

Wolf, S.
Infrarotspektroskopie mittels nichtlinear-optischer Hochkonversion
Aachen, Shaker Verlag, 2018; [Freiburg/Brsg., Univ., Diss., 2017]

RESEARCH DEDICATED TO THE FUTURE

Research of practical utility lies at the heart of all activities pursued by the Fraunhofer-Gesellschaft. Founded in 1949, the research organization undertakes applied research that drives economic development and serves the wider benefit of society. Its services are solicited by customers and contractual partners in industry, the service sector and public administration.

At present, the Fraunhofer-Gesellschaft maintains 72 institutes and research units. The majority of the more than 26,600 staff are qualified scientists and engineers, who work with an annual research budget of 2.6 billion euros. Of this sum, 2.2 billion euros is generated through contract research. Around 70 percent of the Fraunhofer-Gesellschaft's contract research revenue is derived from contracts with industry and from publicly financed research projects. Around 30 percent is contributed by the German federal and state governments in the form of base funding, enabling the institutes to work ahead on solutions to problems that will not become acutely relevant to industry and society until five or ten years from now.

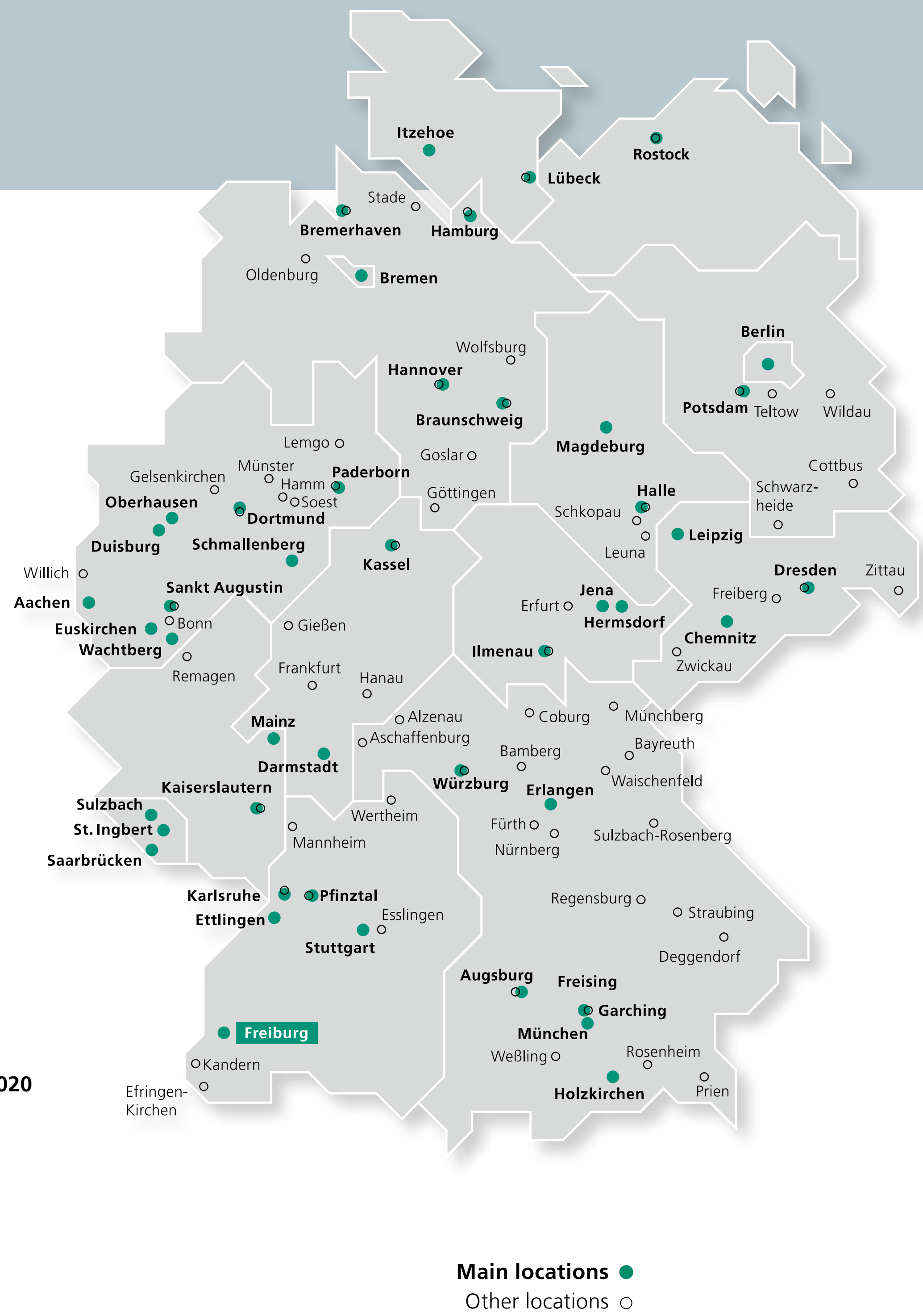
International collaborations with excellent research partners and innovative companies around the world ensure direct access to regions of the greatest importance to present and future scientific progress and economic development.

With its clearly defined mission of application-oriented research and its focus on key technologies of relevance to the future, the Fraunhofer-Gesellschaft plays a prominent role in the German and European innovation process. Applied research has a knock-on effect that extends beyond the direct benefits perceived by the customer: Through their research and development work, the Fraunhofer Institutes help to reinforce the competitive strength of the economy in their local region, and throughout Germany and Europe. They do so by promoting innovation, strengthening the technological base, improving the acceptance of new technologies, and helping to train the urgently needed future generation of scientists and engineers.

As an employer, the Fraunhofer-Gesellschaft offers its staff the opportunity to develop the professional and personal skills that will allow them to take up positions of responsibility within their institute, at universities, in industry and in society. Students who choose to work on projects at the Fraunhofer Institutes have excellent prospects of starting and developing a career in industry by virtue of the practical training and experience they have acquired.

The Fraunhofer-Gesellschaft is a recognized non-profit organization that takes its name from Joseph von Fraunhofer (1787–1826), the illustrious Munich researcher, inventor and entrepreneur.

www.fraunhofer.de



New address as of January 2020
Georges-Köhler-Allee 301
79110 Freiburg

Fraunhofer IPM
Fraunhofer Institute for Physical
Measurement Techniques IPM
Heidenhofstraße 8
79110 Freiburg
P +49 761 8857-0
F +49 761 8857-224
info@ipm.fraunhofer.de

www.ipm.fraunhofer.de/en

EDITORIAL NOTES

Picture acknowledgements

ambrozinio – shutterstock (56)
Christoph Müller/Fraunhofer IPM (38; 49; 50; 51)
David Nadler/Fraunhofer IPM (20 M.)
Felix Groteloh (52)
Fraunhofer-Gesellschaft e.V. (89)
Fraunhofer IOF (19 o.; 69)
Fraunhofer IPM (33; 37; 43; 47; 57; 75; 81)
GINGER - Lehmann + Partner GmbH (42)
Holger Kock/Fraunhofer IPM (Titel; 3; 6; 7; 10; 14; 16; 17; 18; 20 o., 20 u.; 21; 23 u.; 24; 25; 26; 27; 29; 30; 32; 34; 35; 39; 40; 41; 44; 45; 48; 53; 54; 58; 61; 62; 63; 64; 65; 66; 67; 68; 70; 71; 72; 73; 74; 76; 77; 78; 79; 82)
Jenny Korhonen/FindIT (15 u.)
Marc Mueller/dedinag / Fraunhofer (15 o.)
markobe - stock.adobe.com (28)
MEV Verlag (59)
Kai-Uwe Wudtke (31; 55)
Klaus Polkowski (9; 19 u.)
Krofoto/Shutterstock.com (46)
Oticki - shutterstock (60)
Philipp Kirsch GmbH (22; 23 o.)
Tobias Seyler/Fraunhofer IPM (36)
University of Freiburg, Faculty of Engineering (13)

Fraunhofer IPM

Fraunhofer Institute for
Physical Measurement Techniques IPM
Heidenhofstraße 8
D - 79110 Freiburg
P + 49 761 8857 - 0
F + 49 761 8857 - 224
info@ipm.fraunhofer.de

Homepage
www.ipm.fraunhofer.de/en

Youtube Channel
https://www.youtube.com/
channel/UCiSbuFuIa85ryZ5COrlRrZQ

New address as of January 2020
Georges-Köhler-Allee 301
79110 Freiburg

Editorial Address

Fraunhofer Institute for
Physical Measurement Techniques IPM
Communications and Media
Holger Kock
Heidenhofstraße 8
D - 79110 Freiburg
P + 49 761 8857 - 129
holger.kock@ipm.fraunhofer.de

Editorial Team

Holger Kock, Anja Strobel

Design

Adam Lipinski

Translation

Peschel Communications GmbH, Freiburg

Print

Burger Druck GmbH, Waldkirch