expert optical solutions

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Quantitative Imaging & Sensing (QIS)

Department Overview

About QIS

With over 30 years of experience, the Quantitative Imaging & Sensing (QIS) department of ILM specializes in light propagation in scattering media. Our expertise spans several key areas:

→ **Development of measurement devices**
We create devices that accurately determine the optical properties of various media.

→ **Light simulation in turbid media**
We simulate light behavior in complex, scattering materials to better understand and predict optical interactions.

→ **Analytical solutions based on transfer theory**
Our work includes developing new analytical solutions for the transport equations governing light propagation.

→ **Physics-based rendering**
We focus on realistic visualization techniques to enhance the accuracy of digital models.

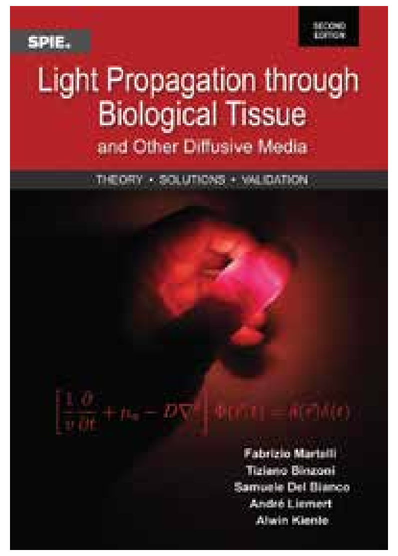
→ **Optical phantom development**
These are crucial tools we design for calibrating and testing medical imaging devices.

Our innovations in these areas are instrumental in advancing biomedical imaging, remote sensing, and optical engineering. By addressing complex challenges in these fields, we improve the precision and reliability of optical systems across various industries. With over 200 publications, including the book *Light Propagation Through Biological Tissue and Other Diffusive Media: Theory, Solutions, and Validations* (2022), we significantly contribute to research and applications in this domain.

About ILM

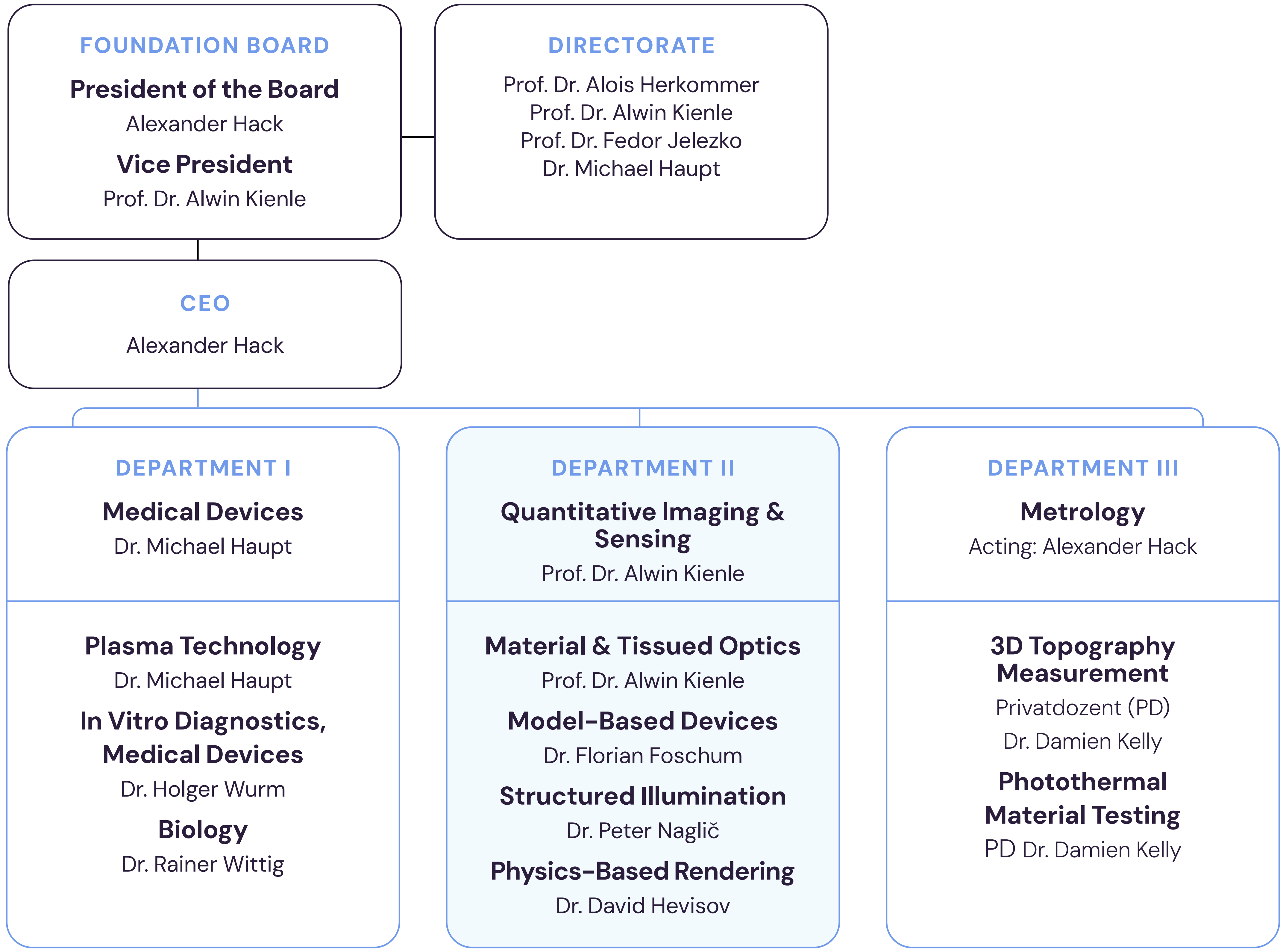
The Quantitative Imaging & Sensing (QIS) department of the Institute for Laser Technologies in Medicine and Metrology (ILM), at the University of Ulm, focuses on advanced imaging and sensor technology research. Established in 1985 as a foundation under civil law, ILM's mission is to bridge the gap between applied research and real-world applications, especially in industrial and medical contexts.

ILM collaborates closely with companies and often participates in publicly funded projects and research and development (R&D) contracts. As a member of the Innovationsallianz Baden-Württemberg, ILM is dedicated to fostering innovation within the region. The institute emphasizes practical research and the development of technologies with a clear path toward implementation, working at the forefront of laser technology applications in both medicine and industry.


SPIE.
SECOND EDITION
Light Propagation through Biological Tissue
and Other Diffusive Media
THEORY • SOLUTIONS • VALIDATION
Fabrizio Martelli
Tiziano Binzoni
Samuele Del Bianco
André Liemert
Alwin Kienle

200+
papers published

Our Team



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Our History

| Scientific Events | Political Events

- 1985 Foundation of ILM
- 1991 Start of activities in tissue optics
- 2000 Beginning of studies on teeth optics
- 2006 Foundation of research group at ILM
- 2012 Spectrally resolved measurement of optical properties
- 2014 Spatial frequency domain imaging
- 2017 Department "Quantitative Imaging & Sensing"
- 2017 Analytical solutions of generalized RTE
- 2018 Full color rendering of three-dimensional objects
- 2020 First commercial setup SphereSpectro, Gigahertz-Optik GmbH
- 2021 Three operating working groups
- 2024 Phantoms with precise optical properties
- 2025 Foundation of ZOE

Understanding Light Scattering in Turbid Media

Fundamentals of light scattering in turbid media

Light scattering is a fundamental optical phenomenon that occurs when light interacts with particles, irregularities, or structures within a turbid medium. Turbid media are materials that, in average, scatter light multiple times, leading to complex light propagation behaviors. These include biological tissues, colloidal suspensions, plastics, and atmospheric aerosols. Understanding light scattering in such media is essential for optical diagnostics, imaging, and theoretical modeling of light transport.

Light interaction in turbid media

When light enters a turbid medium, it undergoes multiple scattering events due to inhomogeneities in the refractive index. Unlike in clear media, where light travels in straight paths, in turbid media, photons experience random deviations, leading to diffusion-like behavior. The degree of scattering depends on several parameters, including particle size, shape, concentration, and the refractive index contrast between particles and the surrounding medium.

Key mechanisms of scattering in turbid media include:

- **Single scattering:** When a photon encounters an isolated particle, it is deflected in a specific direction according to Maxwell's equations. The angular distribution of scattered light depends on the size and and the complex refractive index of the scatterer and its surrounding.
- **Multiple scattering:** In dense media, photons usually undergo multiple scattering events before emerging or being absorbed. This leads to a loss of directionality and results in a diffuse light propagation.
- **Anisotropic scattering:** In biological and engineered materials, scattering is not uniform in all directions. For example, the Henyey-Greenstein phase function is often used to describe forward or backward scattering tendencies.
- **Ballistic and diffuse light:** In weakly scattering media, some photons travel nearly unperturbed (ballistic photons), while others experience multiple deflections (diffuse photons). The ratio of these components determines imaging depth and resolution in optical techniques.

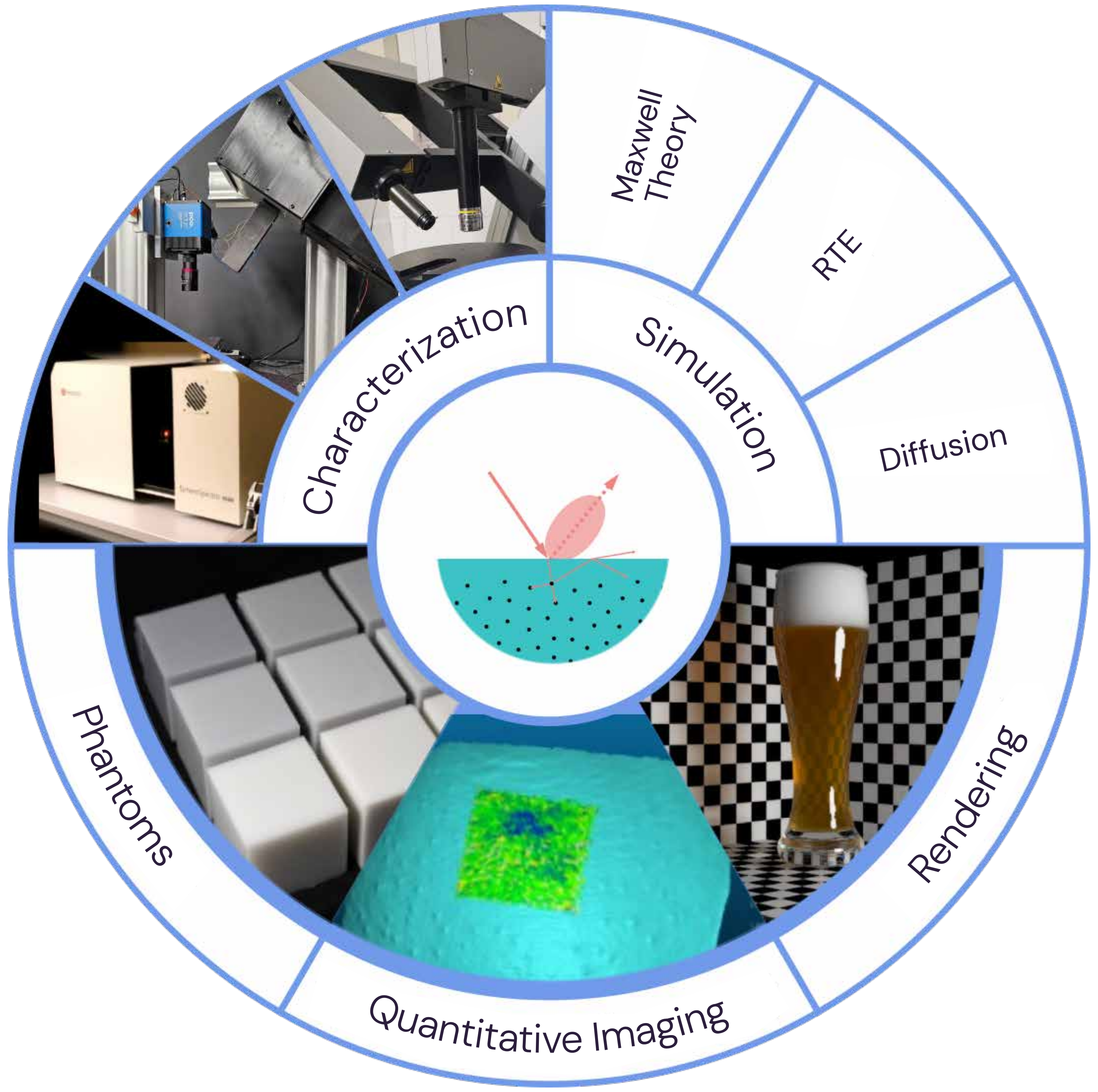
Scattering regimes

The type and extent of scattering depend on the relationship between the particle size (d) and the wavelength of light (λ) (besides the involved scattering indices):

- **Rayleigh scattering ($d \ll \lambda$):** Small particles scatter shorter wavelengths more effectively, leading to a strong wavelength dependence.
- **Mie scattering regime ($d \approx \lambda$):** Larger particles cause a strong angle-dependent scattering with minimal wavelength selectivity.
- **Geometric optics regime ($d \gg \lambda$):** Scattering follows classical optics principles, resembling refraction and reflection effects.

Conclusion

Light scattering in turbid media is a complex but well-characterizable phenomenon that governs optical transport in diverse systems. Understanding these interactions allows for improved imaging techniques, material characterization, and theoretical modeling of light propagation. By studying scattering behavior, scientists can develop advanced optical tools for research and industry.

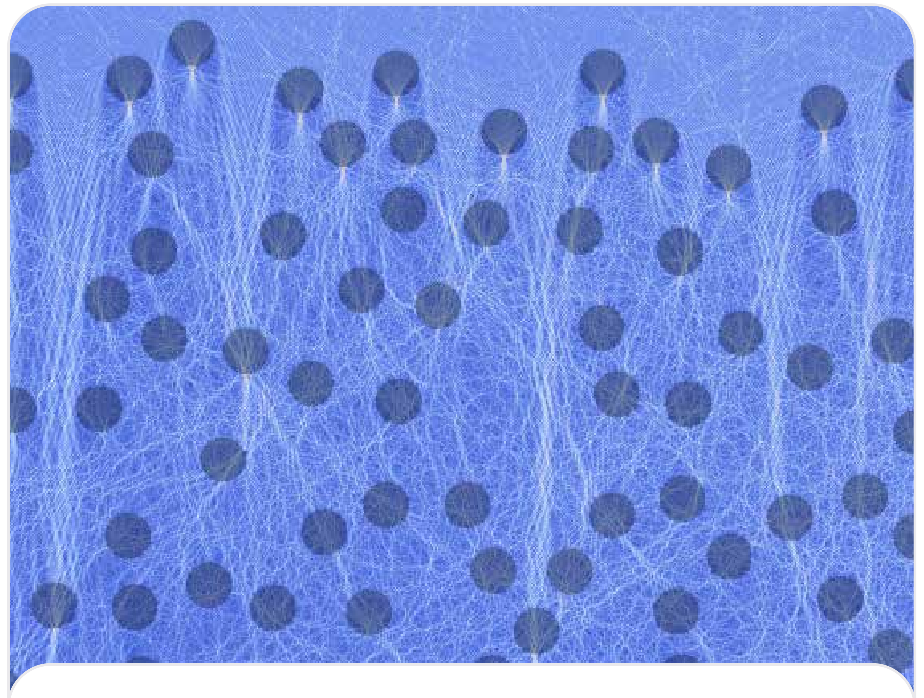


Our Core Competencies and Research Fields in the Area of Scattering Media

Characterization

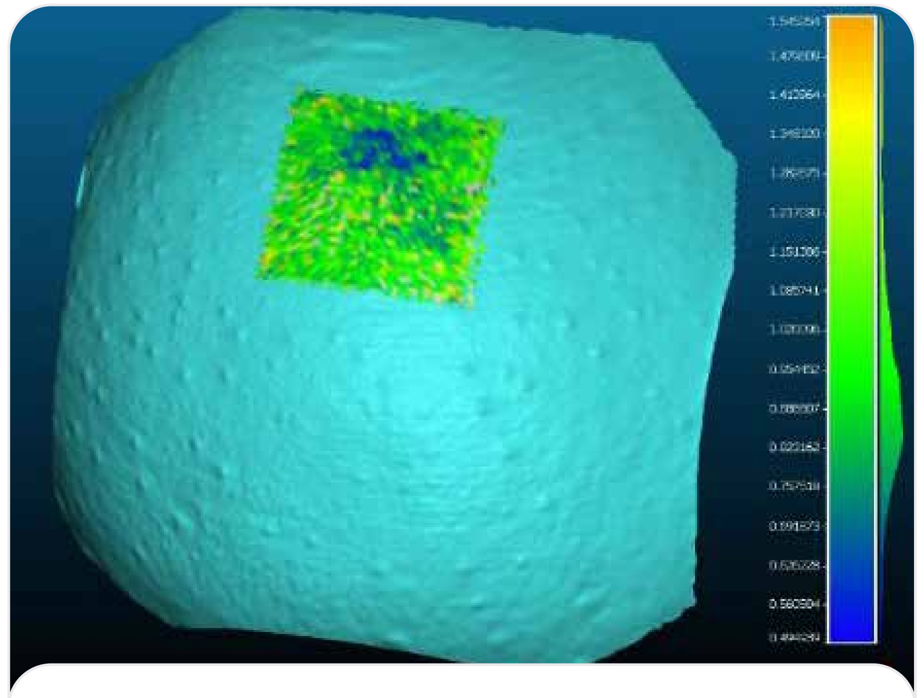
The Center for Determination of Optical Properties (ZOE) offers precise, physics-based measurements across a wide spectral range, from UV to infrared (250 nm to 20 µm). It provides specialized setups for analyzing samples with varying scattering characteristics, from weakly to strongly scattering materials. This enables accurate optical property assessments tailored to diverse applications in medical and industrial fields.

Simulation



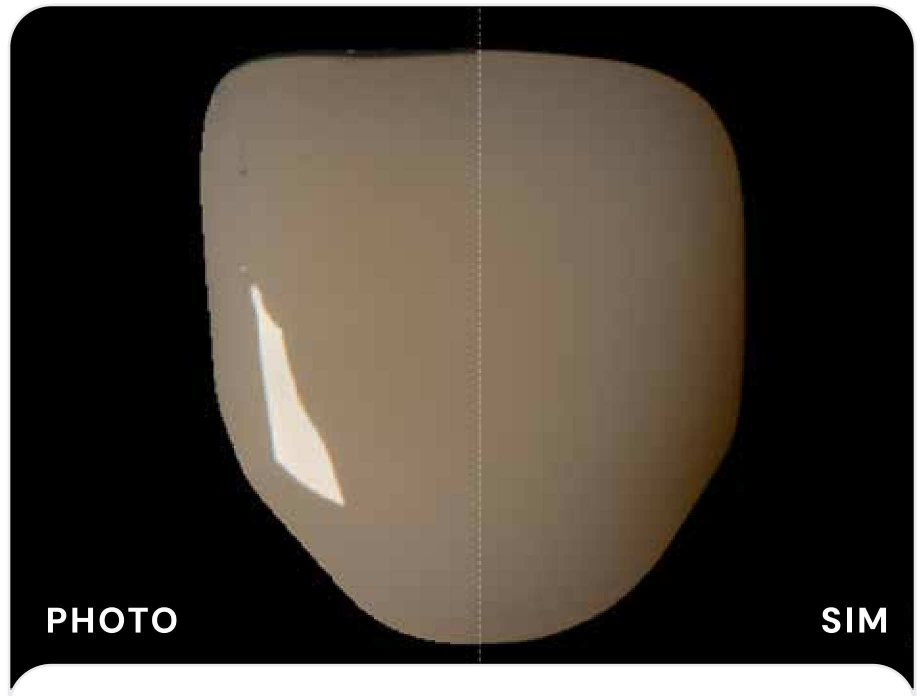
Using Monte Carlo simulations and analytical solutions based on radiative transfer theory (RTE), light behavior in scattering media can be accurately modeled. These sophisticated methods enable precise predictions of light interactions, which are essential for advancements in fields such as biomedical imaging, remote sensing, and optical engineering.

Quantitative Imaging



An advanced imaging technique that provides spatially resolved measurements of optical properties in various media. One example is Spatial Frequency Domain Imaging, which captures local optical properties. By analyzing how light interacts with different spatial frequencies, it is possible to assess the optical properties of tissues as well as their 3D contours, providing insights that are essential for biomedical applications and diagnostics.

Physics-Based Rendering



Physics-based rendering is grounded in physical principles and employs Monte Carlo methods for realistic imagery. It effectively renders translucent materials, simulating arbitrary geometries under defined lighting conditions. This approach accounts for volume scattering, accurately depicting light interactions with complex materials, enhancing realism in visualizations, computer graphics, and digital optical twins for AI applications.

Optical Phantoms

Optical phantoms are designed to mimic light propagation as it occurs in real objects, effectively replicating optical properties such as absorption and scattering. These phantoms can feature complex geometries, are customizable, and are engineered for long-term stability. They serve as essential references for calibration and validation in imaging systems, enhancing accuracy in various applications.

Characterization

Understanding light propagation is fundamental to many optical applications in medicine and engineering. The Quantitative Imaging & Sensing (QIS) department is therefore focused on model-based, simulation-driven, and metrology-based imaging and sensor technologies. QIS's goal is to directly obtain information using physics-based models of light propagation within different media or objects, eliminating the need for calibration measurements. To achieve this, QIS has developed numerous measurement procedures and theoretical methods.

The Center for Determination of Optical Properties, part of the QIS department at ILM, has a similar mission: to acquire data using physics-based models of light propagation in scattering media or objects without the need for calibration. Established with support from the Federal Ministry of Education and Research (BMBF), the ZOE is considered the first center worldwide dedicated to determining all optical properties of scattering media in a broad wavelength range.

The ZOE offers an array of advanced setups to measure optical properties across a wide wavelength range (from approximately 250 nm to 2 µm). These setups enable the determination of the four essential properties defined by radiative transfer theory—absorption coefficient, scattering coefficient, phase function, and refractive index—with high precision. Additionally, the ZOE includes equipment for characterizing fluorescence and Raman scattering and for measuring topography, angle-resolved scattering, and surface roughness. This comprehensive suite of measurement tools supports the ZOE's role in advancing optical research and directly serving industry needs.

APPLICATIONS

- Quality control in food processing
- Product development
- Sensor development
- Plant health monitoring
- Remote sensing and climate studies
- Biomedical imaging and diagnostics
- Cosmetic and dermatological product development
- Soil and mineral analysis
- Water quality monitoring
- Forensic science and art
- 3D printing and additive manufacturing

The ZOE provides a wide range of measurement setups for the determination of optical properties and sample topography:

→ Integrating sphere measurement (VIS, NIR, IR)

→ Collimated transmission

→ Spatially resolved reflectance

→ Spatial frequency domain imaging

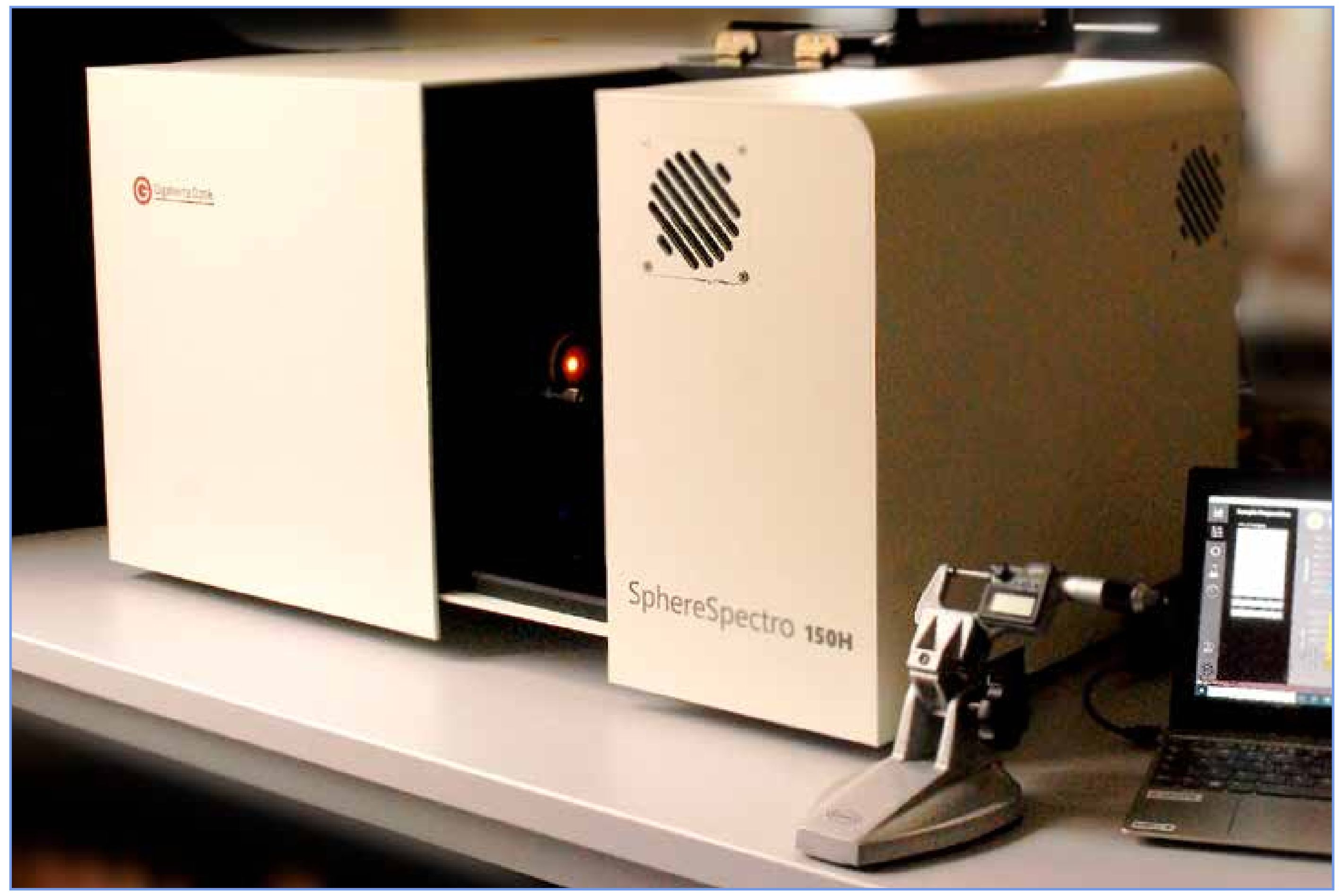
→ Angular and spectrally resolved scattered light measurements in VIS and NIR (BSDF)

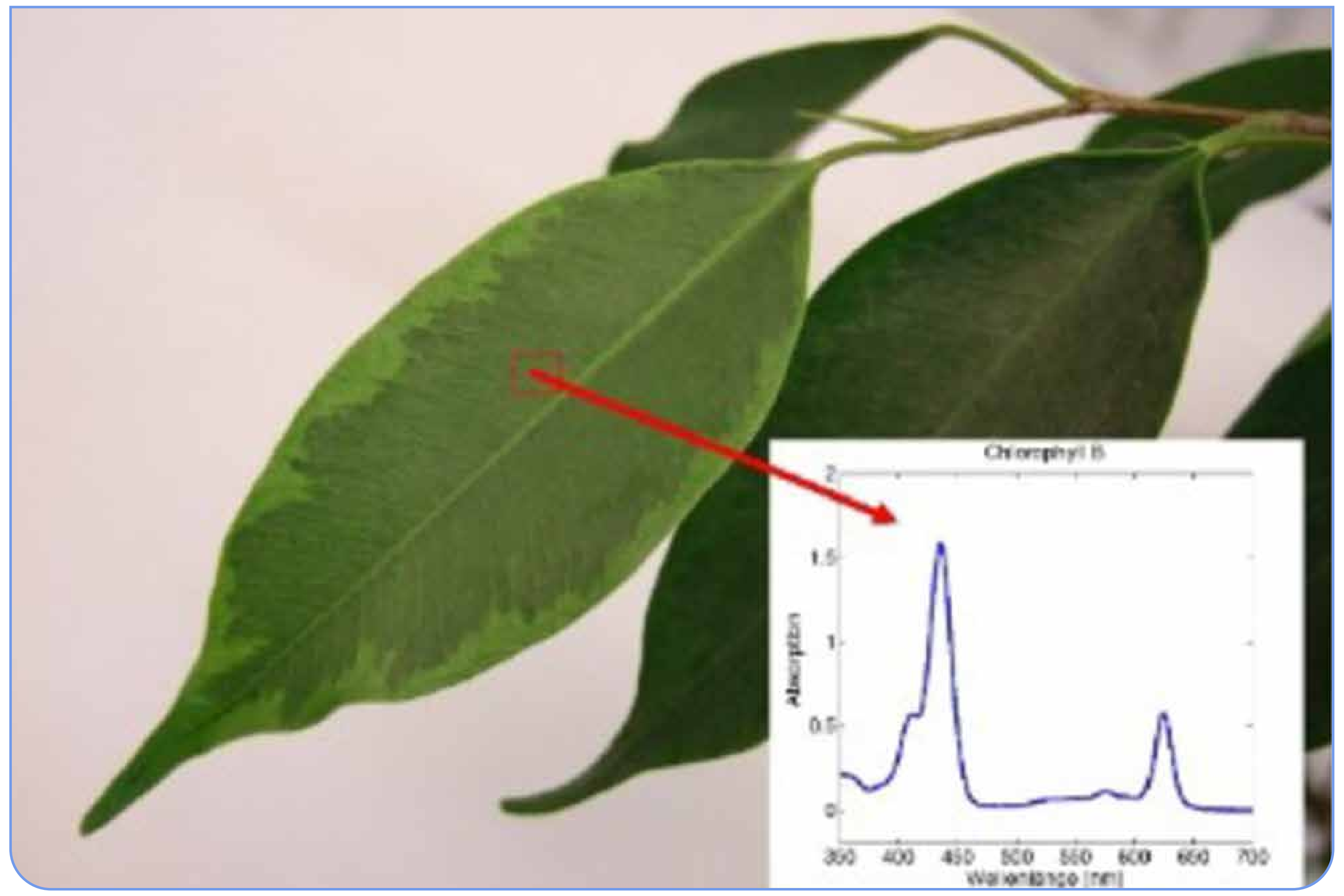
→ FTIR spectroscopy

→ Ellipsometry

→ Quantitative fluorescence spectroscopy in scattering media

→ Flow Raman spectroscopy





Simulations

A key focus of the work at QIS is the quantitative analysis of light propagation in turbid media, conducted in three scales:

Microscopic scale: Maxwell's theory

Mesoscopic scale: radiative transfer theory

Macroscopic theory: diffusion theory

Maxwell's theory is the fundamental theory for describing light propagation in classical physics. At QIS, we have developed and implemented numerical and analytical solutions to the Maxwell's equations. For numerical solutions, a GPU-based FDTD code was created, a PSTD version was implemented, and a novel method based on the Born series was established. Additionally, analytical solutions for various geometries, such as multiple cylinders, were derived. To solve Maxwell's equations, the complex refractive index with a resolution finer than the wavelength of light is required. While all relevant parameters are obtained by these methods, the simulation size is limited to about $(100\ \lambda)^3$ avoiding excessive computation time.

Radiative transfer theory is an approximation of Maxwell's theory that ignores the wave nature of light, allowing for the consideration of much larger volumes. QIS derived the first analytical solutions to the radiative transfer equation for key geometries, such as layered media. Additionally, numerical solutions based on the Monte Carlo method were implemented, accelerated, and validated. These codes can handle arbitrarily shaped geometries with millions of voxels, each potentially having different optical properties. Furthermore, the propagation of polarized light can also be considered. In addition, the microscopic information obtained from Maxwell's theory can be used to describe single scattering rigorously within radiative transfer theory. As a result, anisotropic light propagation in aligned turbid media can be investigated.

Diffusion theory, an approximation to radiative transfer theory, is used because it allows for relatively simple analytical solutions for certain important geometries. At QIS many analytical solutions were derived for a variety of important geometries for the first time, and are partly published in a monograph.

EXAMPLES FOR POSSIBLE SIMULATION APPLICATIONS

Maxwell's theory:

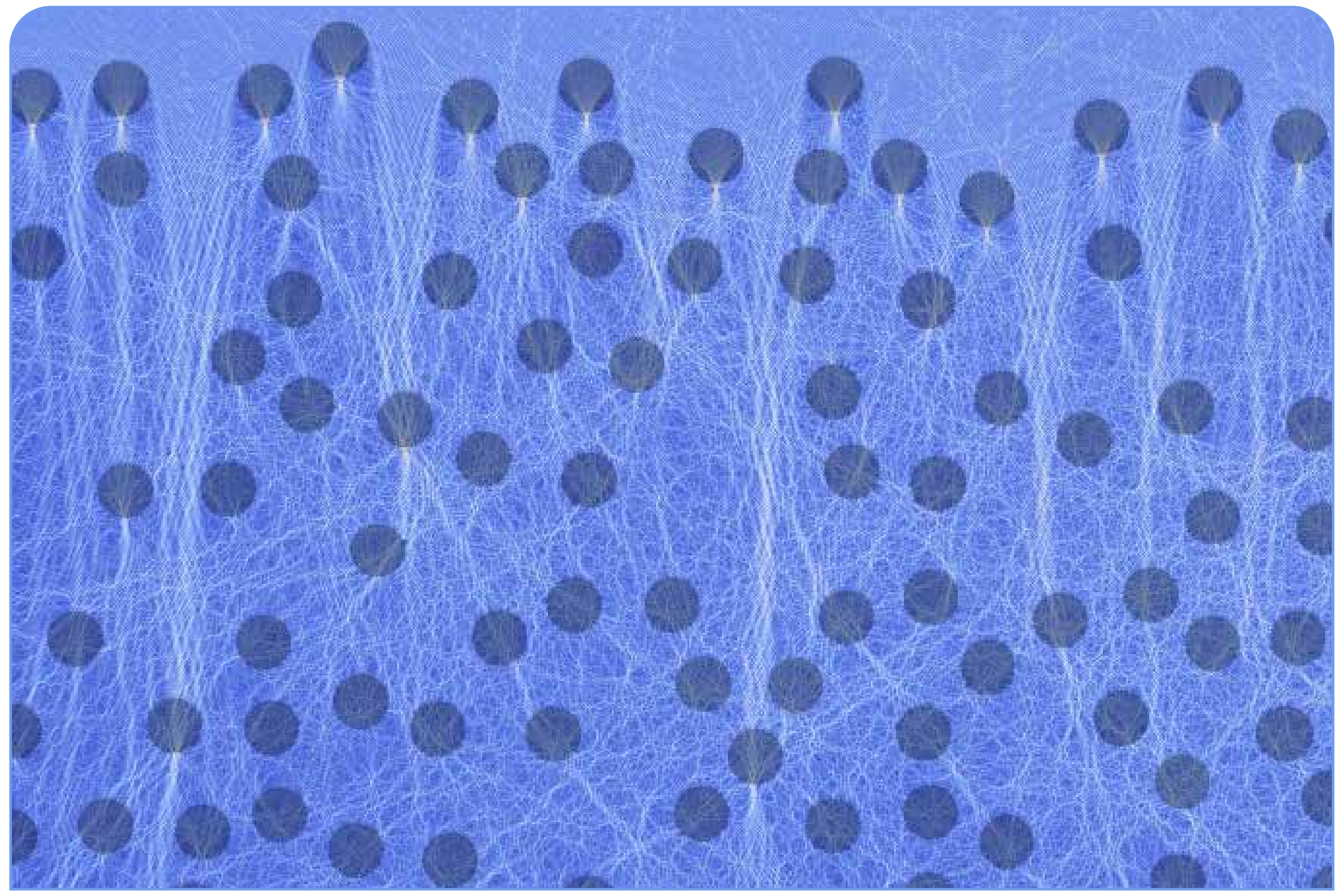
- Optical coherence tomography (OCT)
- Laser scanning microscopy (LSM)
- Wavefront shaping
- Scattering by cells, bacteria, chromophores, etc.
- Single scattering phase function

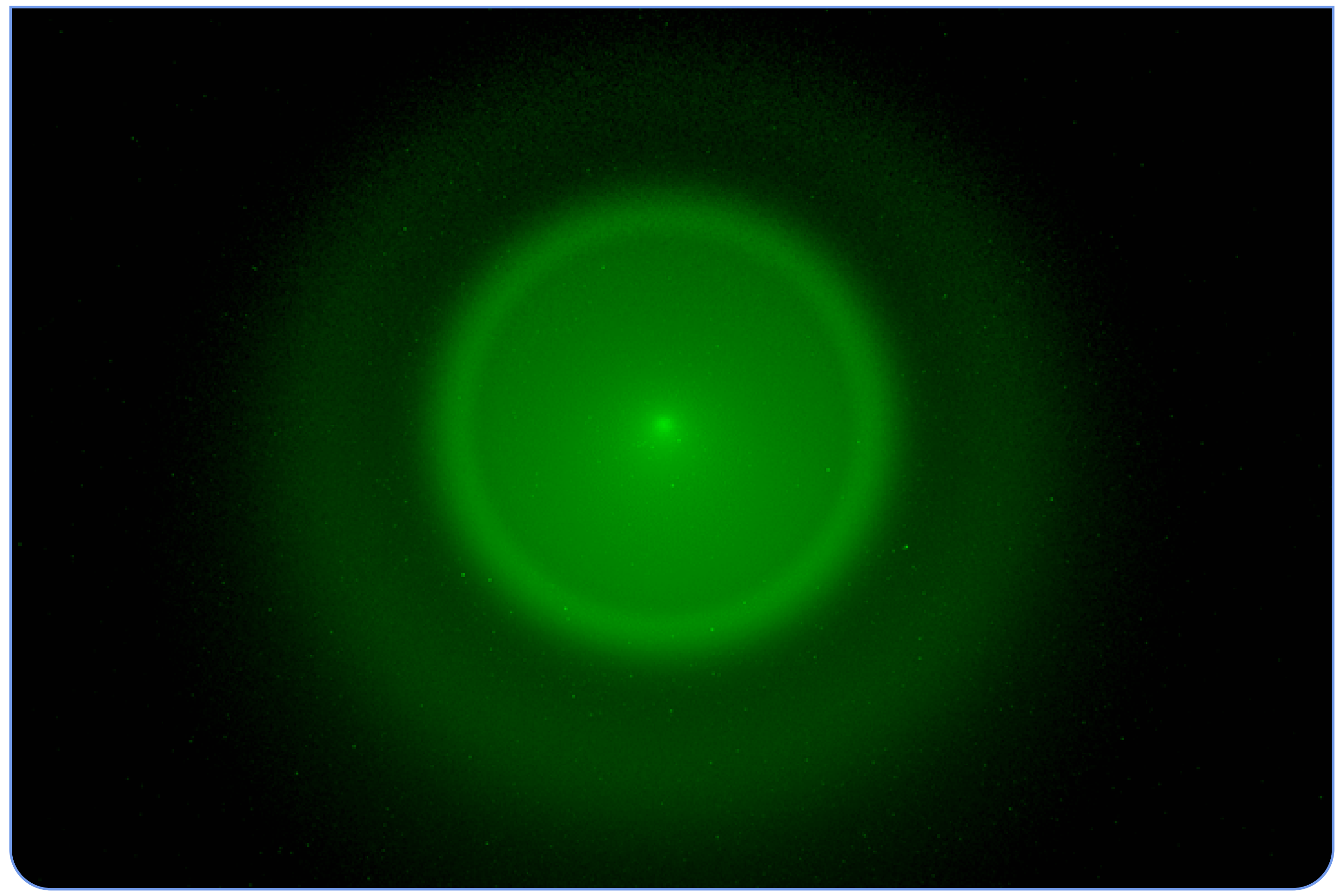
Radiative transfer theory:

- Rendering of teeth and dental restorations
- Simulation of bad weather for autonomous driving
- Dosimetry in photodynamic therapy
- Imaging in the spatial frequency domain
- Laser Doppler spectroscopy
- Coherent backscattering
- Optics in flora and fauna, e. g. light propagation in corals
- Solution of the inverse problem for the determination of optical properties

Diffusion theory:

- Diffuse optical tomography
- Non invasive investigation of brain oxygenation in the time domain
- Determination of blood concentration in muscles



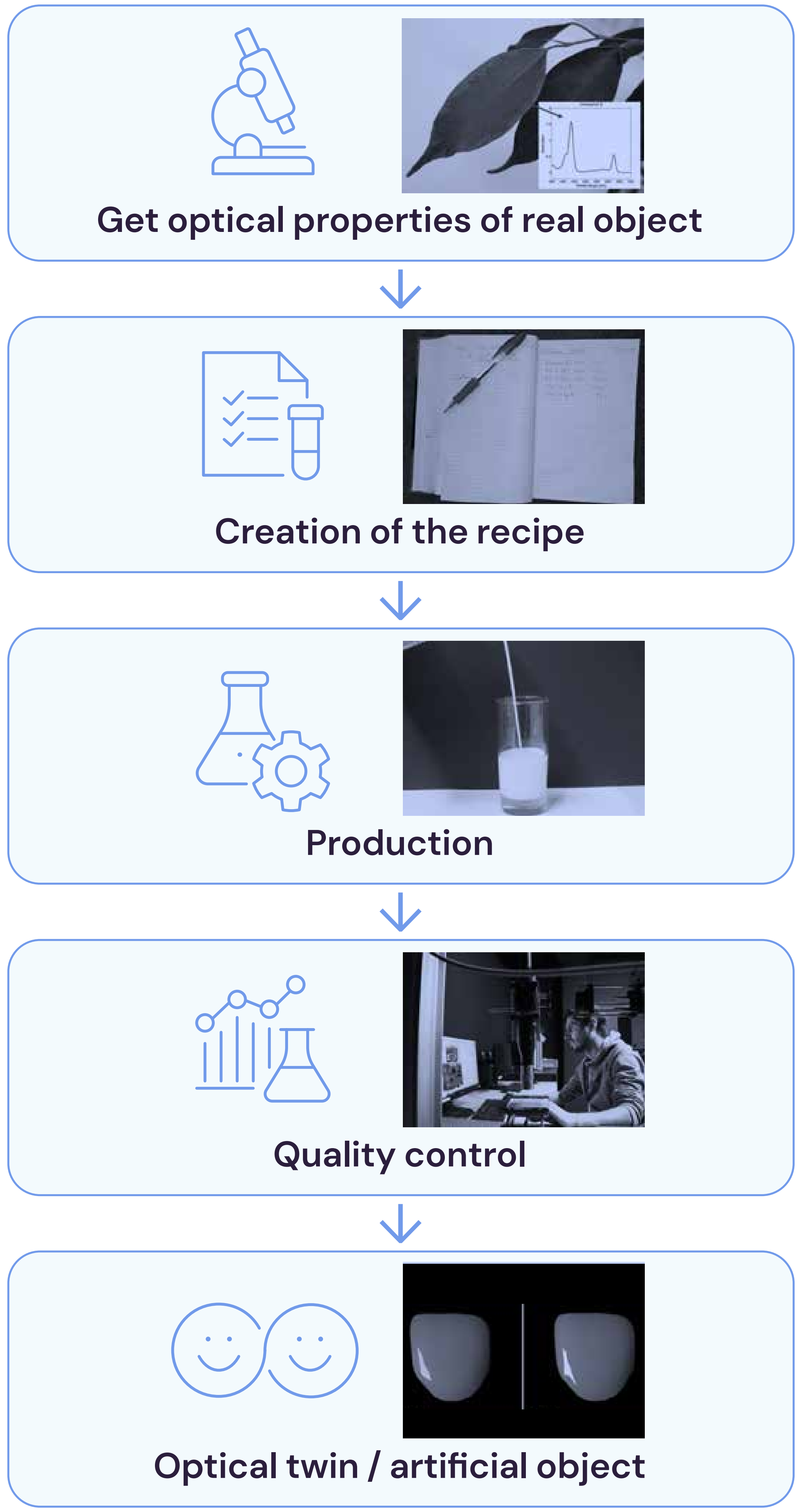


Optical Phantoms

We develop and produce optical phantoms that simulate specific optical properties as artificial models. These phantoms play a central role in research, calibration and quality control, particularly in the fields of medical technology and imaging techniques. We offer phantoms with variable geometry and material composition, tailored to the customer's specific requirements. Homogeneous models can be used, for example, to measure diffuse reflections or transmissions, while layered or structured variants mimic more complex scenarios such as tissue structures. Materials such as silicone, epoxy resins and other highly specialized substances are used, which are precisely adapted in terms of scattering, absorption and other optical properties. The phantoms are primarily used for the calibration of optical devices, for the development and validation of new technologies, and for the simulation of medical scenarios. They are able to realistically simulate specific optical properties of tissues such as skin, fat or muscle tissue. Through careful characterization and material selection, QIS's products guarantee high accuracy and reproducibility of results. Further information about QIS's services can be found on our website.

EXAMPLES FOR POSSIBLE SIMULATION APPLICATIONS

- **Medical imaging:** calibration and quality assurance
- **Research and development**: testing and validating new technologies
- **Laser and photon therapy:** optimization of treatment procedures, e.g. in dermatology
- **Spectroscopy:** analyzing tissues or substances using light scattering and absorption
- **Training:** training medical staff using realistic models
- **Industrial applications:** calibration of optical sensors and cameras
- **Optical biopsy:** development of optically non-invasive diagnostic procedures
- **Material testing:** simulation of specific optical properties
- **Research in biophotonics:** investigation of light-based interactions in biology



Get optical properties of real object

↓

Creation of the recipe

↓

Production

↓

Quality control

↓

Optical twin / artificial object

Quantitative Imaging

Quantitative imaging is an advanced technique that provides spatially resolved measurements of optical properties in various turbid media, offering valuable insights for diverse applications. One of the most notable methods in this field is Spatial Frequency Domain Imaging (SFDI). SFDI captures the spatially resolved optical properties of materials, including biological tissues, by analyzing how light interacts with turbid media at different spatial frequencies.

The underlying principle of SFDI involves projecting a modulated light pattern onto the sample and observing how it is scattered and absorbed. By varying the spatial frequency of the incident light pattern, the technique can map local variations in optical properties such as absorption and scattering coefficients.

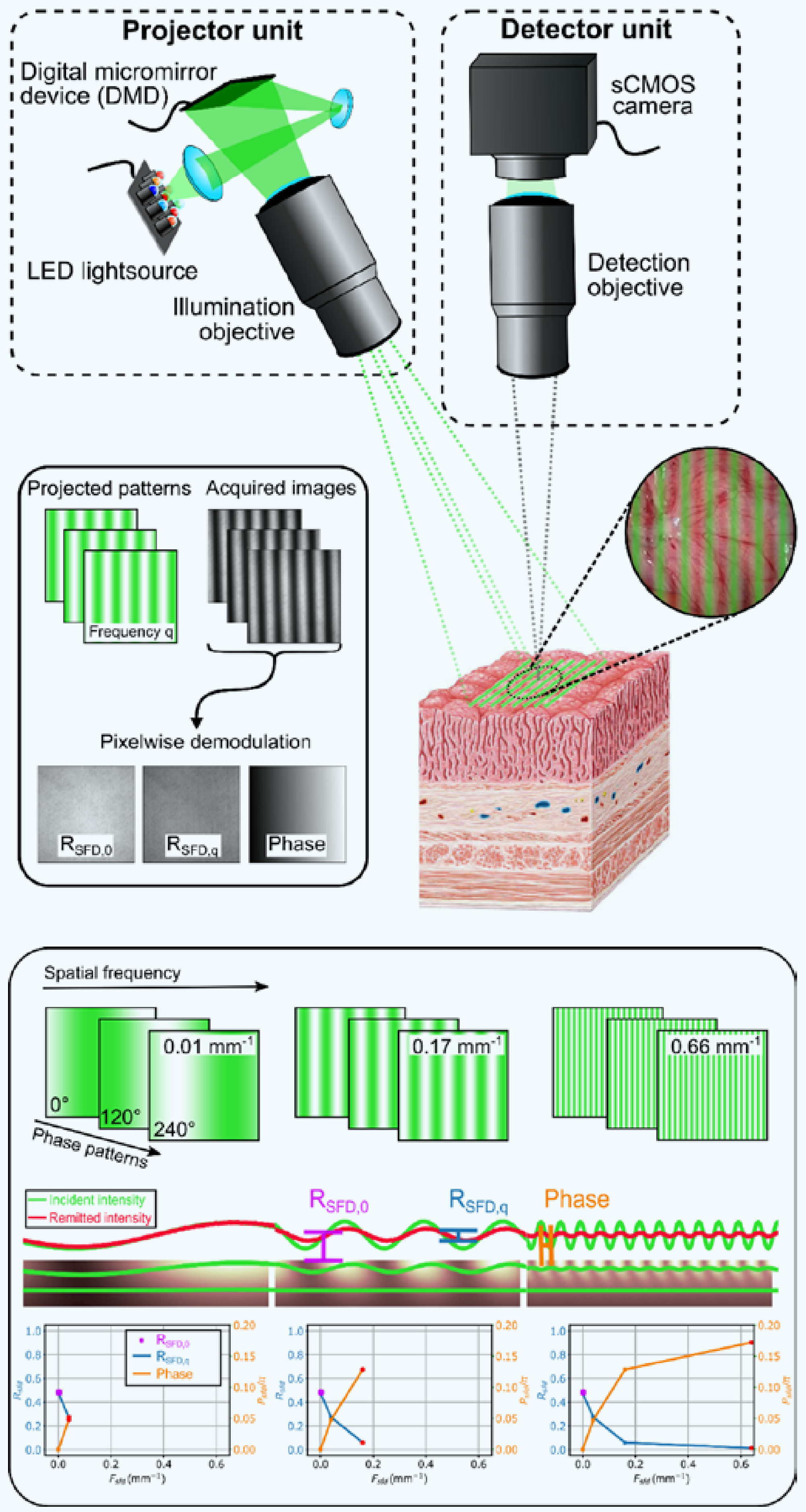
In biomedical applications, quantitative imaging using SFDI has proven essential for assessing the optical properties of tissues. This allows researchers and clinicians to visualize 3D tissue contours, offering a detailed perspective of tissue health and abnormalities. For example, in skin cancer detection, SFDI can help to identify tumors by highlighting differences in optical properties between healthy and diseased tissues.

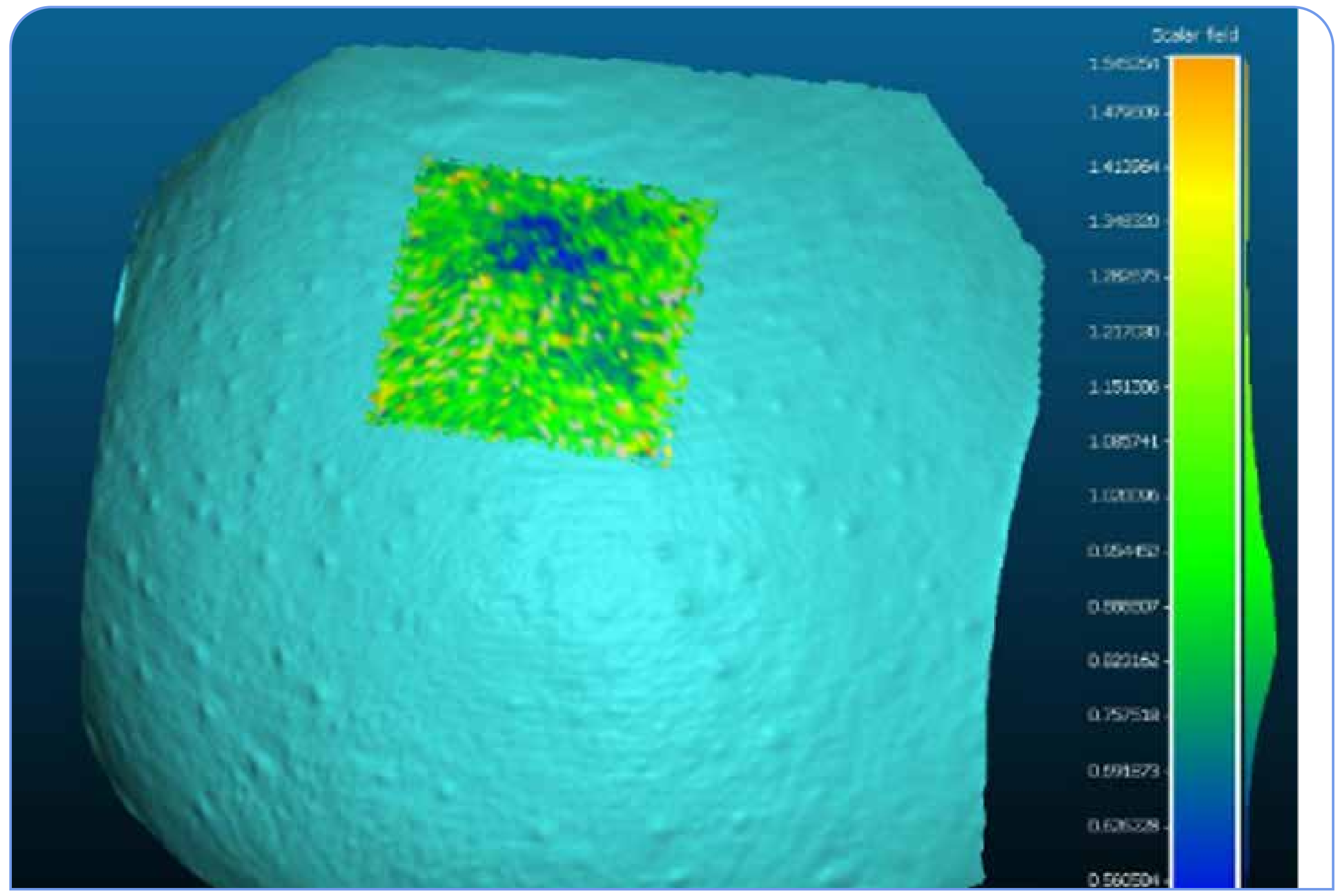
Furthermore, SFDI has applications beyond medical diagnostics. The ability to non-invasively measure the optical properties of tissues at different depths opens up exciting possibilities. In agriculture, quantitative imaging can be used to evaluate the quality of fruits (e.g., apples, strawberries, grapes) before harvest, as well as during storage and handling. In materials science, SFDI is employed to analyze the optical properties of various substances and composites. This can help assess the quality of products like coatings, textiles, and plastics by identifying structural imperfections or inconsistencies.

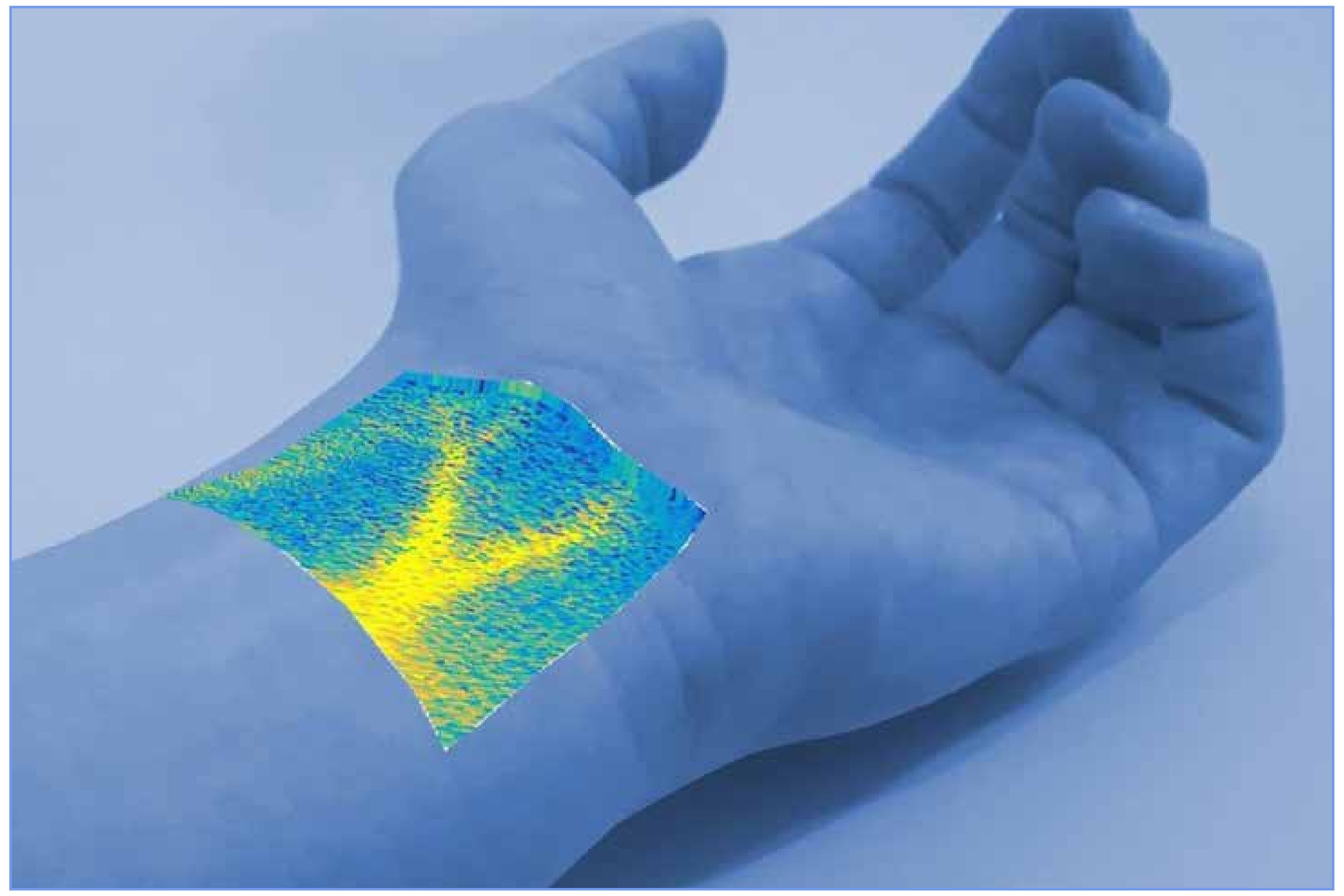
Another application is the use of light scattering to visualize hidden structures below packaging. At QIS, a patented setup enables the visualization of contents through the packaging materials.

In conclusion, quantitative imaging, particularly through SFDI, offers a powerful tool for enhancing the precision and effectiveness of optical metrology, providing spatially resolved optical properties.

SPATIAL FREQUENCY DOMAIN IMAGING







Physics-Based Rendering

QIS's advanced physics-based rendering workflow enables highly accurate color predictions, even for translucent and heterogeneous materials, achieving ΔE values well below 1. By leveraging full path tracing, our self-developed rendering engine incorporates volumetric light transport, such as subsurface scattering, with unparalleled physical precision. This ensures that all relevant physical interactions of light are faithfully simulated, producing results that closely match real-world appearances.

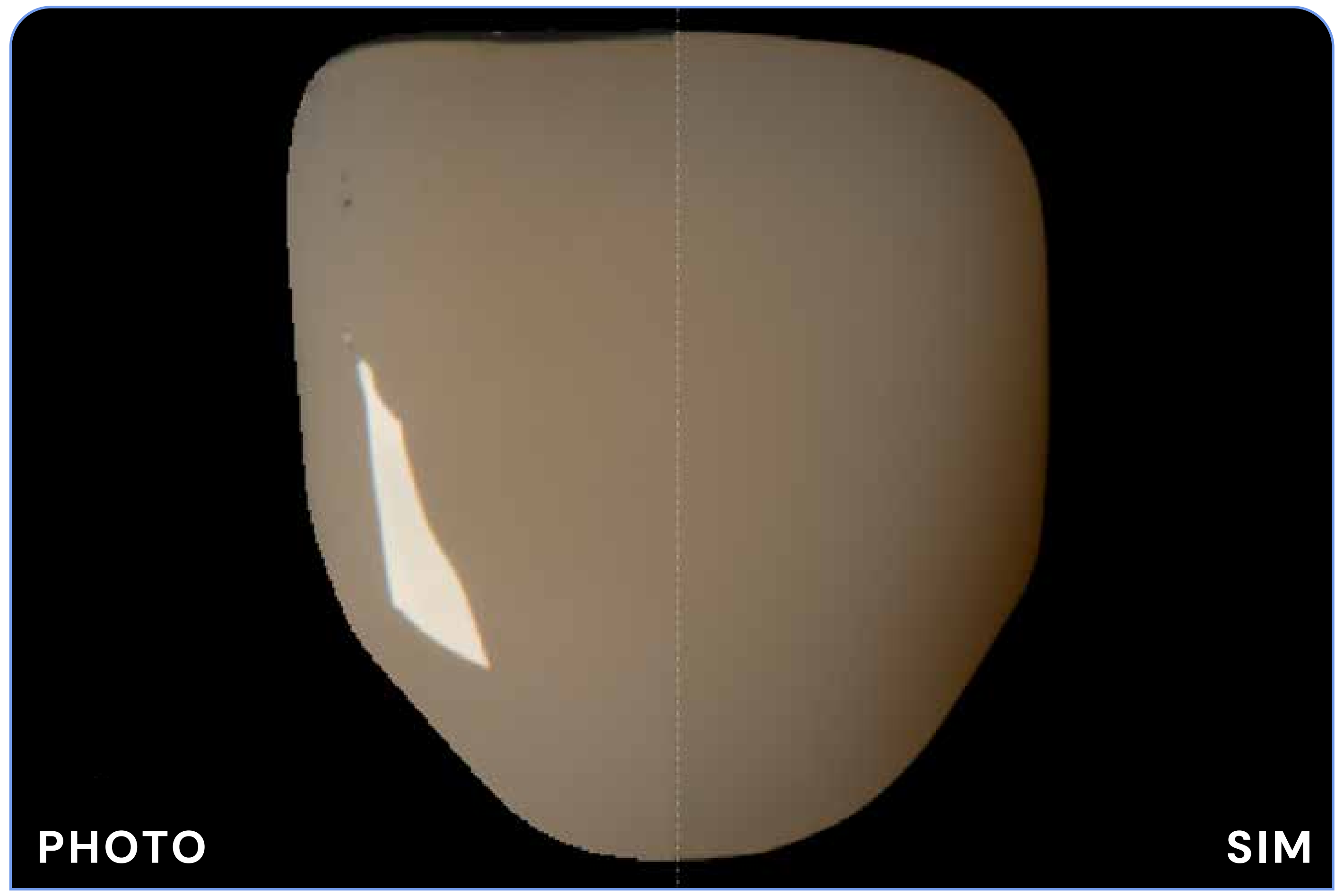
A key advantage arises from the seamless synergy with ZOE: The optical properties required for predictive rendering, as well as the detailed 3D geometry, can be determined entirely in-house with exceptional accuracy before entering the simulation phase. The characterization process involves analyzing the optical properties of all relevant materials using small, carefully controlled test samples, ensuring the highest fidelity in our simulations. Once characterized, we can accurately simulate the color appearance of arbitrary geometries, surface finishes, or material compositions, applying the correct optical properties through advanced physics-based rendering techniques.

This methodology is particularly beneficial for applications requiring exceptionally high color accuracy, such as 3D printing, dental restorations, and color coatings. By digitally optimizing the color appearance of materials and objects before fabrication, our approach significantly reduces the need for physical test prints, iterative prototyping, or manual color adjustments, leading to substantial time and cost savings. Therefore, this predictive capability streamlines workflows, enhances production efficiency, and supports sustainable manufacturing practices by minimizing material waste.

To ensure the physical validity of these calculations, renderings can be rigorously cross-verified by comparing them with their real-world counterparts under controlled conditions in a calibrated lightbox. This verification process helps to validate and refine our models further, reinforcing the reliability and accuracy of our predictive rendering pipeline. As a result, our technology provides a powerful tool for industries that demand the highest level of precision in visualizing and reproducing material appearances before production.

EXAMPLES OF POSSIBLE RENDERING APPLICATIONS

- **Dental restorations:** accurate color matching and material selection for crowns, bridges, and prosthetics
- **3D printing:** predictive color simulation and optimization of printing parameters
- **Artificial intelligence:** generation of high-fidelity synthetic datasets for training AI models
- **Medical imaging:** optimization and modeling via digital optical twins
- **Quality control:** comparison of real-world objects to ideal rendered models to detect deviations
- **Research & academia:** advanced studies in optics, color science, and light interaction with surfaces and volumetric materials



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We offer:

- Laboratory measurements
- Characterization of optical properties
- Simulation and calculation of light propagation in scattering media
- Custom-built scattering phantoms
- 3D topography measurements
- Photometric consulting and support
- Customized measurement solutions

Ask for an offer!

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