Miniaturised optical technology: The challenges of optical design for manufacturing

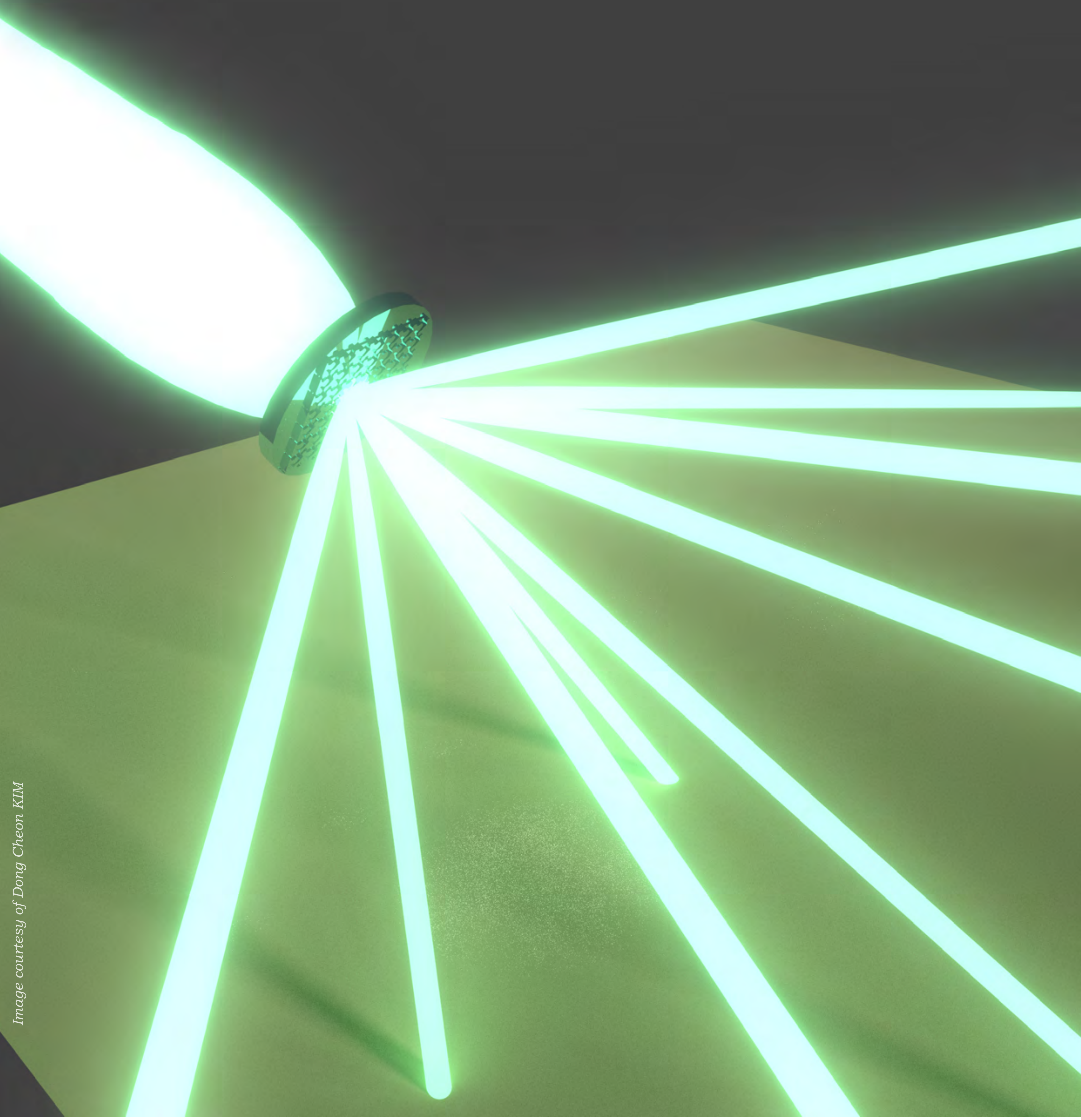

Image courtesy of Dong Cheon KIM

NOLOSS
Lossless photon management
Optical design for manufacture at different length scales

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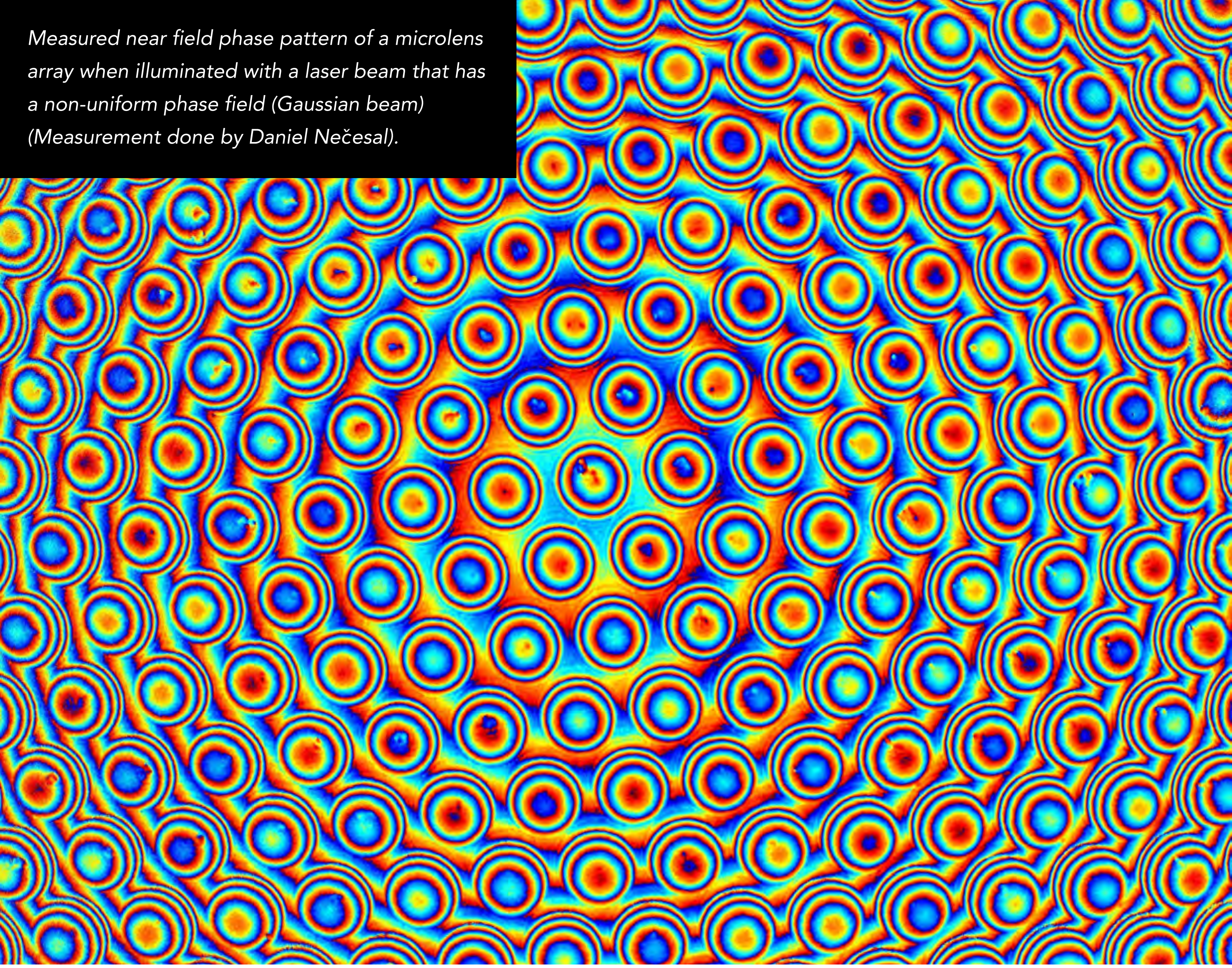


Measured near field phase pattern of a microlens array when illuminated with a laser beam that has a non-uniform phase field (Gaussian beam) (Measurement done by Daniel Nečesal).

Miniaturised optical technology: The challenges of optical design for manufacturing

Toralf Scharf from the NOLOSS Project focuses his research activities at the École Polytechnique fédérale de Lausanne on interdisciplinary subjects bringing micro-system, material technology and optics together. Here, he explains the fascinating topic of miniaturised optical technology, including the challenges of optical design for manufacturing

Microlens arrays with a size of about 30 microns and arranged in arrays present a very challenging situation for modelling. If a system has a millimetre dimension with several thousand lenses, many parameters need to be considered. If one adds non-uniform illumination and the fact that physical optics principles like diffraction have to be taken into account, then even the most advanced simulation tool will have difficulties to describe the optical properties close to the structures (near field) and far from it (far field) correctly. This is a typical situation where modern optical design lacks fabrication technology that has no problem to deliver such systems. (Microlens array from SUSS Microoptics Neuchâtel, Switzerland, www.suss-microoptics.com)

Modern optical technology

Often the term “modern optics” is linked to the rise of laser technology, which has changed the world. All high-technology equipment we use today has a certain connection to a laser. Might it be because lasers are used for its fabrication or the laser is the core element of making it work? Certainly, laser technology is still the main innovation driver in modern optical technology today. This is due to the fact that lasers have gained efficiency in recent years and their handling is well understood and they are broadly accepted as a safe and reliable light source by the public. With the advent of laser technology, new theoretical concepts of optical design become known, the tools of modern optics.

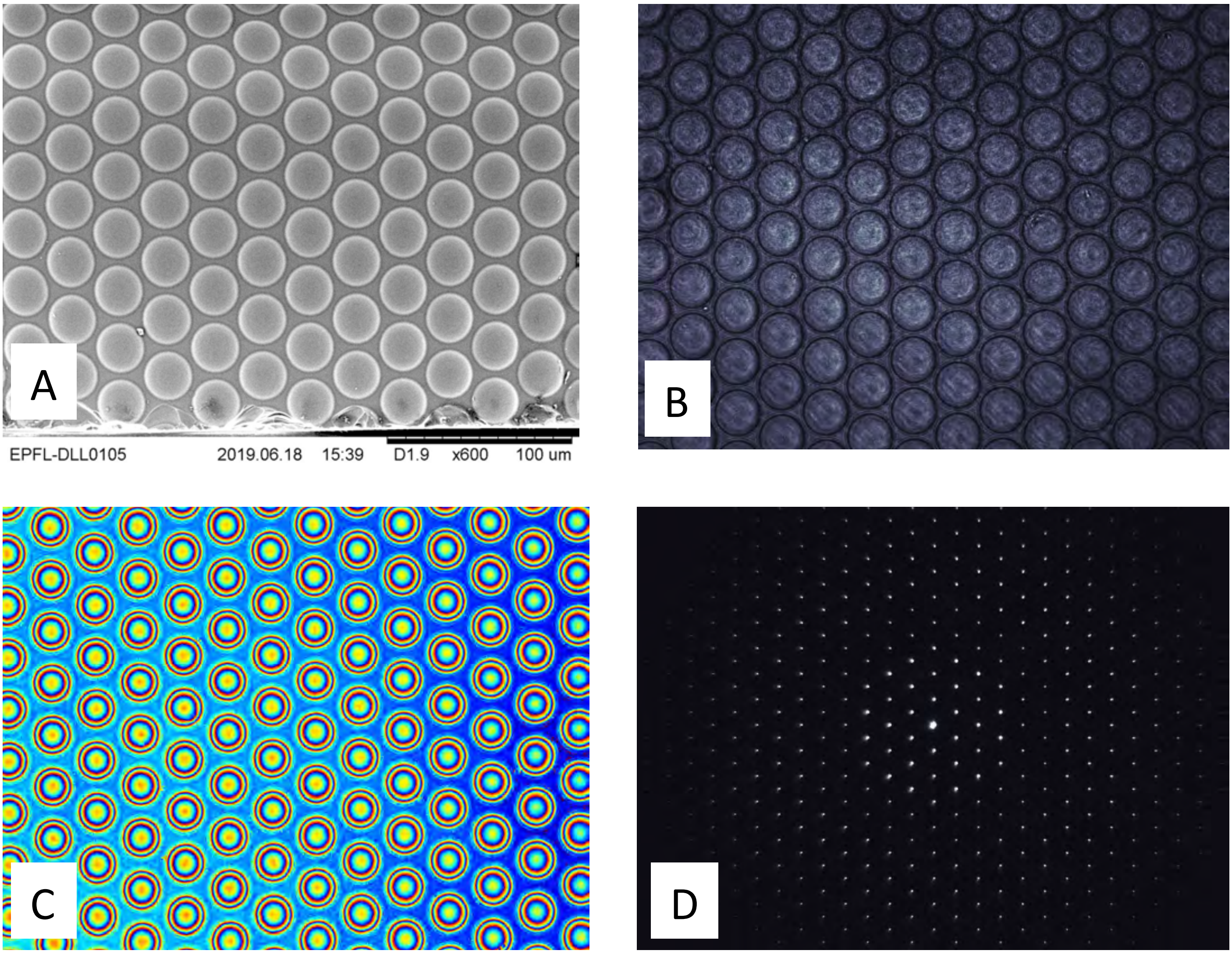
Laser and their technology today are described by quantum optics to understand its operation and special tools were created to describe the propagation of laser light. All this is a story that dates about 50 years back and the question then comes up, what will be the next technology revolution that will change optics? In our opinion, the revolution comes from the optical design of miniaturised optical systems for mainly for two reasons: First, the computational power of today’s calculation machines allows us to use sophisticated models and more complex solving strategies to find a solution to problems that could not be challenged previously. Second, the change in technology from a single element approach to the more integral fabrication on wafers and the advents of additive manufacturing, which will lead to device performance per volume that could not be imagined before. If we speak of device performance per volume, the main objectives for many systems are implicitly stated: miniaturisation and performance.

Before giving any more details on new trends, we need to step back to discuss developments from a historical perspective, focusing on optical design trends and manufacturing developments. For more than a century, optical design was based on ray tracing. It means that the path of light rays is considered as coming from an object, going through an optical system and arriving at an image or analysis plane. This has become a very powerful technique. The success is based on the ever-increasing number of rays that can be used by today’s computers but also on the fact that analytical analysis tools developed a long time ago are easily implemented into that picture. If one likes, modern ray tracing is taking a theoretically approved method to an extreme performance by extending precision. The strength of the approach is that a high-level theory developed for optical design and aberration analysis can be used for interpretation of the result. This interplay between an analytical description (with formulas) and simulations of performance with any desired precision, leads to incredible high-performance optical designs for instance of camera or microscope objectives. It can also be applied to rather unusual problems, like light field camera analysis. But the multi-parameter design space of classical optics and the always finer spacing of information by a higher number of pixels of imaging devices, such as a camera, overcharges on some models. The result is that some effective optimisation and analysis of advanced optical functionality becomes harder and harder. A way out of this design crisis can be the description of problems not only with simple rays but as Lightfields that carry spatial and angular information which is just enough to treat the actual design challenge. The basic idea is to use the effective sampling in space, angle, time and signal to create the ultimate performance by design. One of these concepts is based on the plenoptic function, a description proposed a long time ago but nowadays it is increasingly used to analyse system performance, especially for imaging.

The plenoptic function describes the complexity of optical information that can be acquired by an optical system. It represents the intensity of light as a function of position, direction, wavelength and point of observation of the light rays. The application of the concept in plenoptic imaging embraces several non-conventional imaging techniques aimed at sampling the plenoptic function or slices of it with a plenoptic camera, a camera that uses several layers of imaging to record information. A standard plenoptic camera is composed of the main lens and an array of microlenses. A typical example of microlenses is shown in the image where a lens array with more than 1,000 lenses per square mm is shown. With such an array, many imaging channels are formed and each channel can easily be optimised with ray tracing techniques. The quality of the final result, however, cannot be described with standard aberration theory as the final images are recomposed from many sub-images of a multichannel system. In such a case, the strength of ray tracing, combining high- level aberration theory and in detail analysis of ray tracing images to understand the limitations of the system and interpret its quality and potential, is lost. New approaches are, therefore, needed and tools such as Nodal aberration theory might help to conceptualise complex problems with field dependent aberrations of multichannel systems.

But not all problems can be treated with ray tracing models. Especially if optical systems are miniaturised, the light field closely behind the optical elements shows particular features that are difficult if not impossible to include in ray tracing algorithms. The problem is that rays are no longer the correct description of the situation. One needs to consider fields, hence locally varying values of quantities that describe the light properties. Such fields have the strength (amplitude) and coordination in time (phase) that must be considered. Although the simulation of such fields is possible by so-called rigorous methods, including them in the design path of optical systems is often difficult. The link to the high-level theory description as one has it for ray tracing cannot be established and one misses a convenient analysis tool such as the aberration theory. In an application scenario, often the description of the situation switches between fields and rays and allows to profit from both approaches: having the field information to gain precision for miniaturised optics and describe the outcome with a ray optical analysis. This setting has the advantage of being flexible and allows to connect to real-world situations. A real-world situation is characterised by the fact that the interfaces used for man-machine interactions are macroscopic and described by ray optics. In short, the hybrid simulation provides information of local fields and one converts the output to rays to connect to macroscopic components on the detection plane. While for the second part, concerning the ray description, all details are known it is different for the first step of the analysis of the fields. Interpretation of the influence of the field close to the structures and how small changes will modify the final result are not always possible because there is no coherent description comparable to aberration theory for near field problems. This problem is best understood when discussing a few examples.

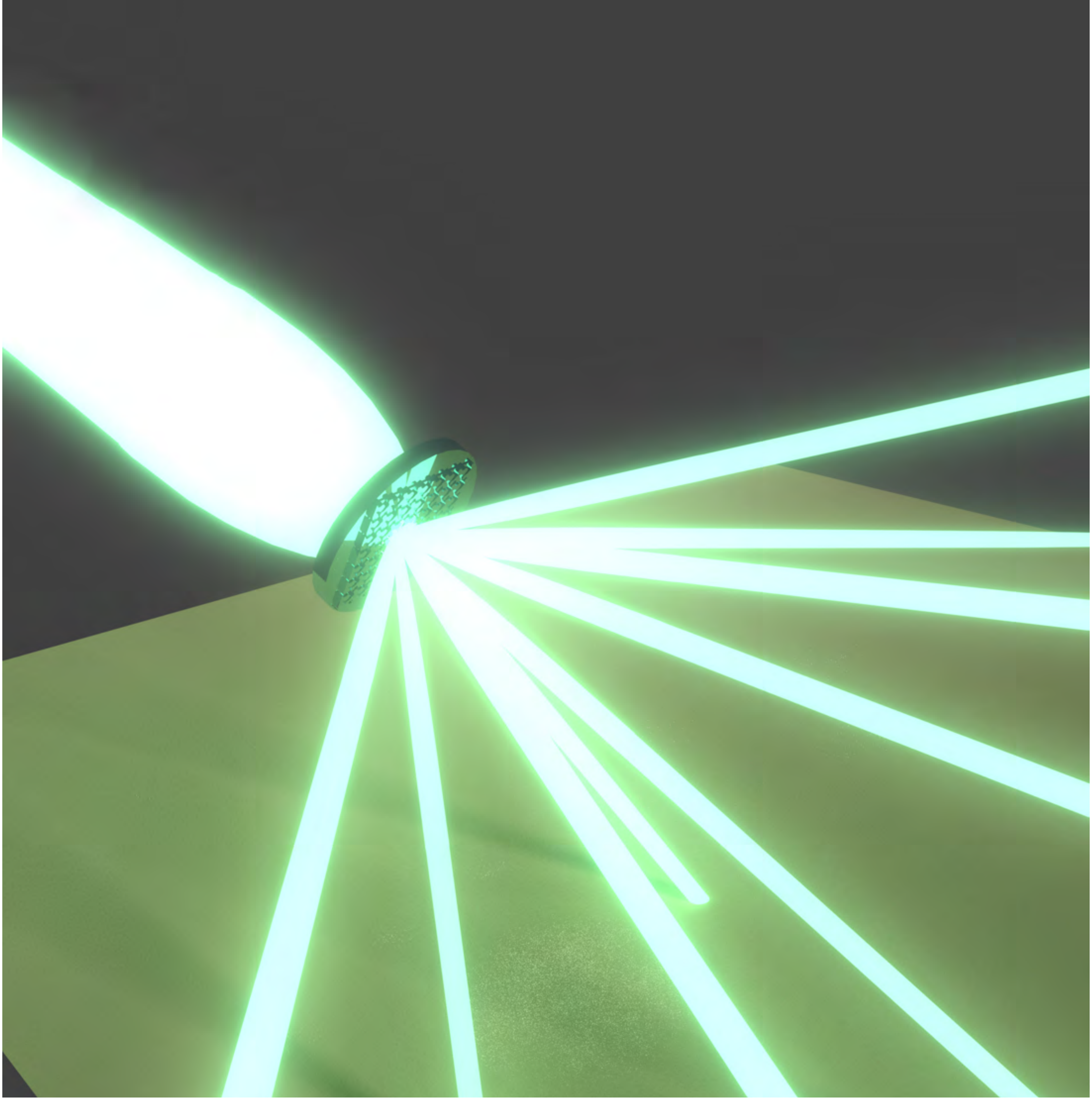
In diffractive optics, incoming light fields are modified by a thin microstructured surface with small structures and very high precision. In the plane, the structures are defined with an accuracy of less than 50 nm and have a typical size of less than one micrometre. Usually, no losses are accepted and the elements do not modify the amplitude of light but only the phase. Phase modulation is implemented by a varying height profile. If light propagates through such a structure, the result will be a very complicated modulation. Although there is no absorption or loss in the element the result will be a function of the phase and amplitude of the field. A simple model would not account for the amplitude change and will be of very limited use only. Such simple phase models have the advantage to be completely deterministic and would allow including the diffractive optical element in a design chain based on ray optics. But the result will not be correct and cannot satisfy the demands of today designers. A more sophisticated or accurate model needs to be used. The most accurate models that exist are based on rigorous calculation and have the advantage to work for



Optical response of microlens array under plane wave illumination. The phase and amplitude of the light fields after the structures defines the light pattern that is found far away behind the object. ***A****) Scanning electron microscope image of the microlens array (obtained from Suss Microoptics). Diameter is 27 micron.* ***B****) Light microscope image of the microlens array.* ***C****) The phase of the light emerging from the microlenses when illuminated with plane wave provided by a red laser and measured with an interference microscope.* ***D****) The light pattern caused by diffraction far away from the microlens array when illuminated with a laser pointer.*

forward or backward propagation but not at the same time. Hence, they are not as deterministic as the simple model. Such unidirectional propagation situation makes the design process very difficult. The results are optical components where each element is designed for a specific case and no general statement can be made.

Furthermore, there is no design scheme, as we know it for the aberration theory in the ray model, that would help us to analyse outcomes and judge the potential of structure for further improvement. The challenge of the next designer generation will be to search for new methods and theories to improve this situation. First, pathways to challenge the classical design path of diffractive optical elements by forward only propagation methods are visible in the adjoint field method. But there is still a long way to go until formalising a higher-level description of



the design in miniaturised optical systems. The influence of methods and tools coming from computer vision and representation of data will help to accelerate this development.

And there is the situation when even fields with amplitude and phase would not be a convenient way to describe the interaction of light with objects. This is mainly the case if confinement is considered. With confinement, we mean that light is trapped either between mirrors in the resonator or in small particles or nanostructures of a particular material. In such cases, the field description leads to the possibility of interpreting it as modes. A mode (or sometimes called resonance) is a state of the system that is usually unique and can be often excited with interaction from outside fields. If one likes, it is a different interpretation of the situation where a complicated field exists under the assumption that one can decompose the field in a sum of states with different strengths and time coupling – the modes. In this description of light, one leaves the description of fields with their amplitude and phase and gives each mode strength and phase.

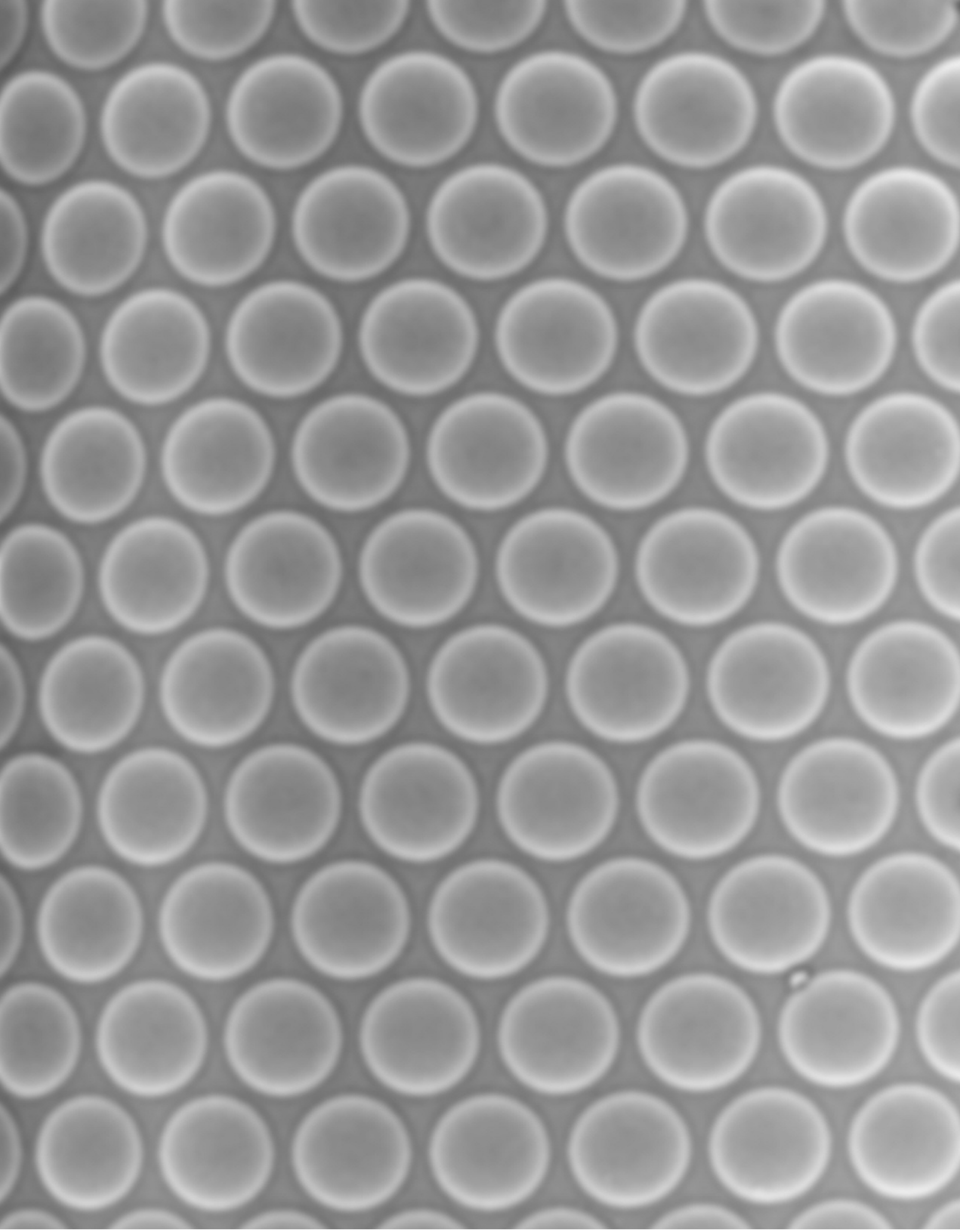
Coupling factors between modes and the outside fields are used for describing systems and their interactions. One can get the impression that this is a very complicated situation but it is actually not. Once the mode profile is known, the calculation can be based on abstract models like the hybridisation of energy states and simple coupling relations between modes. What is very complicated, is to get the shape of modes and a proper description of the set of modes that are useful. Here, we find a situation back as we have in ray description and aberration theory. A high-level description exists with mode coupling that allows design under almost any circumstances ones the modes are known. There is, nevertheless, an important difference between the ray model and the mode description: the modes are different for each system while the rays serve for many cases. To overcome this difficulty, mode descriptions can be largely standardised for similar geometries and cases providing a solid base to deal with the sophisticated situation and complex problems.

The challenges of modern optics technologies lie not only in simulation for a miniaturised optical system. Bridging the gap between design and fabrication is of utmost importance. One of the often-underestimated situations is the change in fabrication technology. In the last century, the basis of optics fabrication for lenses was established. New optical materials were introduced and assembling techniques refined. Components were assembled piece by piece and care was taken to align and adjust the system correctly. In our days, we have seen the introduction of a new class of fabrication technologies based on parallelisation. Because of the need for miniaturisation, it becomes increasingly difficult to hold a single component. Solutions to use wafer level assembly have been developed that are based on arrays of elements. This opens a new world to parallelisation of manufacturing because many process steps are taken for all systems at the same time and once. Precision should be high and testing after each fabrication step becomes important. It needs to ensure that a high production yield can be maintained. One needs to keep in mind that the correction of errors, is still possible for single system assembly, which will not work for wafer level processing. A single error and the whole batch of optical systems are lost. Therefore, a design methodology that takes into account specific aspects of the new fabrication methods and can be used for tolerancing, needs to be applied. To do so, the reliability and speed of simulation tools are needed. The golden rule for modern optical design when it comes to manufacturing has not yet been found. This is especially true for micro-optical systems that get more and more popular with its problem of multidimensional design containing small micron size structures on millimetre size dimensions, so the situation is very challenging. The way towards a unified description has to be found to create a lossless system design for manufacturing.

Toralf Scharf focuses his research activities at the École Polytechnique fédérale de Lausanne on interdisciplinary subjects bringing micro-system, material technology and optics together. With a background in surface physics (MSc), physical chemistry (PhD) and profound experience in optics, he is familiar with all necessary aspects of technology development and application and can communicate with different scientific communities. In over 20 years of project execution with industry and governmental organisations, he has accumulated the right experience to lead and execute the project at different levels.

Toralf Scharf
Senior Scientist/Faculty Member

Funding
This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 675745.



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