Optical Design and Simulation

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Design, Simulation and 3D printing of complex micro-optics

S. Thiele, S. Ristok, H. Giessen, A. Herkommer

3D printing of optics by femtosecond direct laser writing offers unique opportunities for the design of complex micro-optical systems. Since there are barely any restrictions in terms of geometry while feature sizes of <200 nm together with a sub-µm accuracy and a RMS roughness of <10 nm are achievable, an almost arbitrary distribution of refractive and diffractive power in 3D becomes possible. While this absence of restrictions allows the design of highly complex optical devices, the optimum solution is more difficult to find because of a drastically increased parameter space [1]. The aim of our work is to find methods and improve available tools in order to facilitate the search for an optimum solution.

On the size scales of our optics, diffractive effects can play a dominant role, especially if they are part of the optical function as for example in case of 3D-printed gratings, diffractive lenses or holograms. At the same time common approaches for simulation and design like the “thin element approximation” are not valid anymore if such structures are written onto curved surfaces.

As an ideal candidate for the wave-optical simulation the wave-propagation-method (WPM) [2] has been investigated. The algorithm uses the angular spectrum approach to propagate forward scattered scalar fields in split steps.

Figure 1 shows a comparison of the ray-optical and wave-optical model for a telephoto doublet lens in 2D. In this case, both methods are equally suited for an accurate simulation and deliver very similar results. However, as soon as surface imperfections have to be taken into account or the aperture stop gets very small, the raytracing model will be inaccurate if these features are on the size scale of only a few wavelengths. In this case, the WPM offers a computationally efficient alternative.

Since 3D direct laser writing is a very flexible process, short prototyping times can be achieved in comparison to traditional methods. This means that designs can be tested and improved with many iterations in a reasonable time frame.

Fig. 2 shows the example of an aberration corrected 3D-printed doublet lens with a field of view of 40° and an effective f# of 1.35. In Fig. 2A, a microscope image is displayed. Fig. 2B depicts an image captured by this lens. It shows distortion free imaging and a flat field.

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Compound microlens systems for foveated imaging

S. Thiele, K. Arzenbacher, T. Gissibl, H. Giessen, A. Herkommer

3D printing by femtosecond direct laser writing can be applied to a variety of different substrates including CMOS imaging sensors [1]. This enables the fabrication of complex microlens systems directly on chip. We used such an approach to combine multiple lens systems with different focal lengths and to create a foveated imaging system (fig. 1) [2].

Figure 2 shows the working principle: Images from different lenses are combined such that the object scaling stays constant which ultimately leads to an increased resolution in the center of the field of view.

The sub images can directly be read out by the image sensor after 3D printing. Fig. 3 compares imaging results before and after image fusion for different objects. The foveated image features a considerably increased resolution in the center of the field of view.

Figure 3: Measured results from the CMOS imaging sensor [2].

The footprint of one system consisting of four doublet lenses is below 300 x 300 µm² while the height is <200 µm. This high degree of miniaturization can be useful for many fields of application e.g. endoscopy, optical metrology, optical sensing, or security.

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Smartphone-microscope

Widespread diseases like malaria tropica, sickle cell anemia and loiasis need microscopic examination. With the aid of integrated complex camera modules, modern smartphones can be used for diagnostic purpose. Mobile phones are widespread in industrial, as well as in emerging and developing countries. In combination with optical systems and a diagnostic software, smartphones enable a diagnosis in remote regions. This can help to reduce the medical costs and more important save lives at poor places. The images also can be sent to skilled medical staff for an accurate diagnosis.

There are several possibilities to turn your smartphone into a microscope. The simplest way is to attach a lens (with a low focal length) in front of your smartphone camera. We use this lens as an objective. The smartphone camera (tube lens) focuses the collimated light on its sensor. The simplest and most cost-effective method is to use another smartphone camera module. This allows a full field bright-field examination of the sample. A possible optical design of the smartphone microscope with a reversed camera module is shown in fig. 1. Smartphone camera modules are made of several individual designed aspherical lenses and have only small imaging errors.

We used an iPhone 5S camera module to implement the smartphone based microscope. The complete module (see fig. 2 [A]) costs (depending transport costs and range) between 2 to 4 euro. We removed the optical module (see fig. 2 [B]) and used it as an optical head in front of the smartphone camera. Mechanical devices have been constructed for holding the optical module in front of the smartphone camera.

Those devices also help to position and hold the sample at the microscope’s working distance. The manufacturing of these holders has first been realized using a 3D printer. A selection of images taken from standard specimens with the smartphone microscope is shown in fig 3.

Because many biological objects are largely transparent, phase-sensitive imaging methods were investigated in combination with smartphone microscopy. Among the investigated methods are holography as well as the phase contrast microscope.

We used the schematic structure shown in fig. 4 [A] to record an in-line hologram with a smartphone. To ensure the spatial coherence from a LED we used a pinhole. The smartphone’s sensor record the interference pattern. The recorded hologram and its reconstruction is shown in fig. 4 [B] and [C]. To record the original image, we used the angular spectrum implementation of Rayleigh-Sommerfeld’s diffraction integral.

Another method to record phase objects at an increased contrast is the phase contrast microscopy. We made a mechanical design which allows transparent objects to be imaged and subsequently displayed directly on the smartphone display with high contrast. The required phase plate was produced at the ITO.

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Building kit for realization of optical systems

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Photonics is found in many important areas of modern society. It is a basic competency to produce smartphones, cars and airplanes. Many technologies like data transmission with fibers networks, LASER diagnostics in medicine or energy-efficient lighting with LEDs and OLEDs would not work without modern photonic technologies. Photonics offers a significant cross-section technology to deliver innovative solutions to the markets and challenges of tomorrow.

The idea of the BMBF-Project “BaKaRoS” (Baukastensystem zur Realisierung optischer Systeme), a building kit for realization of optical systems, is to announce the topic “photonics” to a wide society. To achieve this goal, we will develop a hardware modular system combined with an open source expert and simulation program (see fig. 1). Those components help the audience (students, interested laypersons and industry users) to build simple and complex optical systems independently and at low cost. The core of the project consortium (fishertechnik, T-Systems, Fraunhofer IAO, Institut für Technische Optik) provides the necessary knowledge from all relevant fields of the project. Associated partners along the value chain (Zeiss, Qioptiq, Sick, Holoeye) address the developments and the organization of the open photonic community, but also add the view of industrial users and suppliers of optical measurement technology.

The basic system consists of existing, standardized and inexpensive building blocks with different optical functions. With those components, it should be possible to realize many different optical setups for a wide range of applications. The basic system will be directly compatible with the leading professional optical system (microbench). This will ensure that cost-effective systems as well as high-quality superstructures can be realized. The selection and position of the components is automatically controlled by an open source expert and simulation system. To proof the problem-solving potential of the modular system different application examples from the fields of smart home, health and industry will be realized. Open innovation approaches for the long-term beneficial cooperation between science, business and creative citizens under the vision “open-photonics-ecosystem” will be analyzed and implemented. On the system’s web-based platform users can contribute and discuss complete solutions as well as subsystems. Thanks to the open-source implementation, dedicated users can continue to expand the hardware components as well as the software for operation (e.g. imaging processing). The implemented expert system uses a consistent modular design. Ultimately three main areas are essential: Kernel (ray tracing as well as optimization), Photonic programming language and User Interface (see fig. 2).

Fig. 1: Solution approaches, target groups and partners of the BMBF-project BaKaRoS.

The implementation for the basic functionality takes place in C++ to achieve the highest possible target group of ambitious hobbyists. The interface can be from Windows, Mac, OS X and Linux.

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Design and measurements with the phase space analyzer

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In illumination design usually a large number of rays must be traced to get accurate results. This is necessary to get information about the integral radiometric quantities. The phase space concept [1] is another way on looking at the mapping of radiance patches from the source to the target in a phase space diagram, as illustrated in fig. 1.

How to observe this mapping? Experimentally, the phase space analyzer [2] provides an easy way to observe a one dimensional radiation field directly in position and angle. With the help of slit apertures and cylindrical lenses the experimental setup can be realized in the lab. We used the setup to analyze different optical systems. Figure 2 illustrates the measured phase space distribution of a hyperchromatic lens. Spherical and axial chromatic aberrations are nicely visible in phase space and agree well with Matlab simulations. Quantitatively the angles between the colours are measured to get the axial chromatic aberrations [3].

We also used the experimental setup to get the phase space diagram for a total internal reflector (TIR) in [4].

Instead of only analyzing the radiance distribution an optimization can be performed. In the design software ZEMAX we can attach a virtual phase space analyzer behind the optical system. Then we define a number of reference rays at the input and observe and control their position in spatial and angular direction at the phase space analyzer exit. The radiance patch attached to each ray will then be mapped according to the reference ray on the target. For example demanding an equidistant separation between the reference rays at target and choosing a Gaussian distribution at input, as illustrated in fig. 3, the resulting optical system will resemble a Gauss to Top-Hat beam shaper. In addition, the optimization does not only allow to control the spatial shape, but also the angular behavior (e.g. tolerance on laser tilt), since the complete phase space volume is optimized.

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Head mounted displays (HMD), as one type of wearable device, are nowadays widely employed in aviation, video, 3D gaming, and training. From the concept point of view, HMDs can be categorized into two types: Virtual Reality and Augmented Reality. The HMDs projecting only computer-generated images are called Virtual Reality. The augmented type HMDs, or see-troughs, display both virtual image and real-world views. We present novel optical design concepts for folded HMD geometries, all based on freeform surfaces.

Generally freeform surfaces offer more capacity to correct particularly off-axis aberrations. Therefore they are widely employed in decentered and tilted systems [1, 2]. Additionally, today’s highly developed single diamond turning technology allows for manufacturing complex freeform surfaces for imaging applications.

The total internal reflection (TIR) prism type geometry described in [3], and illustrated in fig. 1, represents a basic design type for HMD optics, which is widely developed by later designers.

This concept is employed as a reference. In contrast, our investigation [4] also considers catadioptric HMDs and prisms with different reflection folding geometry. These two types of HMDs are seldom investigated and may have mechanical disadvantages; however, the optical performances of these two alternate types are rather fine, since they offer better performance and larger field of view as compared to the reference.

The designed optical systems and the corresponding MTF are shown in fig. 1-3. In fig. 1, a re-optimized reference prism geometry, with one TIR surface, similar to the patent lens is presented. In fig. 2 we illustrate a catadioptric system with one lens and two mirrors. An alternate prism-geometry without TIR surface, but with different folding geometry is depicted in fig. 3.

The performances of our designs are all better than the original patent lens. Moreover, the performances of the two prisms in fig. 1 and fig. 3 are excellent. All fields are diffraction limited or close to being diffraction limited. Compared with these two prisms, the performance of the catadioptric type is worse and the size is relative larger. However, the weight might be attractive, as only a thin lens and two mirrors are applied. Note that for all design we only use two anamorphic surfaces and the highest order of the aspherical terms is 6, which is beneficial for the manufacturing complexity.

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