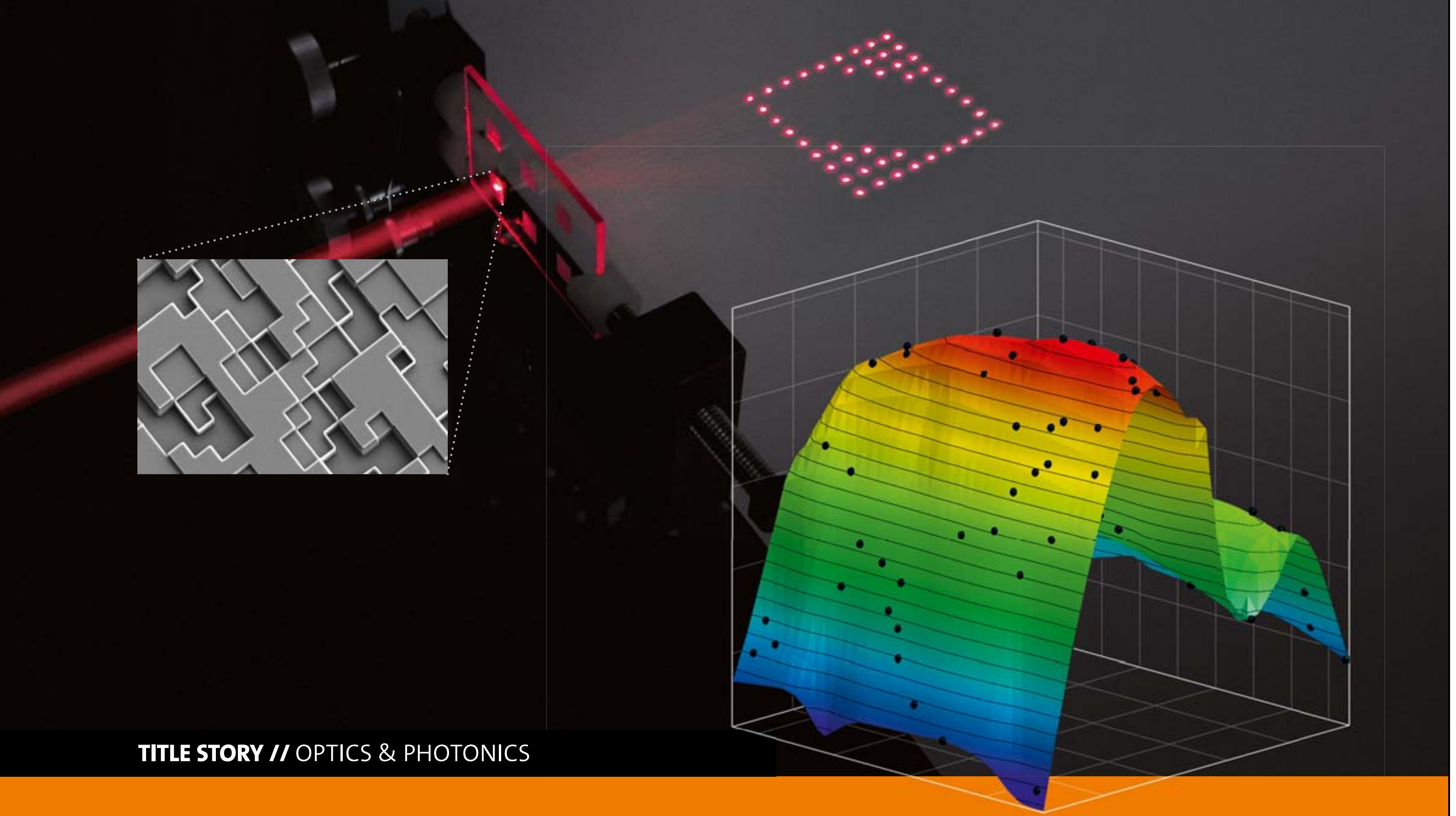

INNOVATION IN OPTICS AND PHOTONICS – VIRTUALLAB AND OPTISLANG

The combination of both tools enables a fast and reliable design of optical systems, design understanding, multi-objective optimization and robustness analysis in a fully automated manner.

Light is essential for our life on earth. We see our world through light; plants and currently also humans generate energy by light and more and more technical developments need and use light to perform certain tasks. The discipline which deals with the physics and the development of devices to harness light in order to perform useful tasks is referred to as optics and photonics, although both terms are used in a somewhat redundant way.

In general, optics and photonics is understood as a technical enabler; this means it is typically an indispensable supporting part within a larger system. A laser and the optics to deliver the light to a workpiece in a fabrication robot is an example of such a combination. Virtual and mixed reality glasses and displays rely on optics but also on a lot of mechanics, electronics and computer technology. The production of modern electronic chips by lithography and wafer steppers is unthinkable without high-end optical technology as an enabling part of the fabrication process. In the car industry, smart and ambient lighting is another trend which benefits from the amazing developments in optics and photonics in recent decades. Think about the backlight illumination and the camera in a cell phone. In medicine, not just optical microscopes, but also modern optics enters more and more the operating theatre as a tool for surgery. We would further like to mention the tremendous progress in flexible contact and intraocular lenses in the huge ophthalmic optics market. We could add numerous other examples which demonstrate the impact of optics and photonics on modern technology and our daily life. Optics is understood to be an enabling technology in the basic fields of, for example, information technology and telecommunication, healthcare and life sciences, optical sensing, lighting and energy, national defense, industrial manufacturing, and fundamental R&D.

A typical optical system consists of a technical light source or a light-emitting object, optical components which shape and control the spatial and temporal characteristics of the emitted light and components which transport the light from A to B where it is then used to perform some required effect or where it is detected to obtain information about the light-emitting object or some other sample on the way through the system. We mainly distinguish between imaging and non-imaging optical systems. An imaging system deals with providing the detector, e.g. the human eye or the

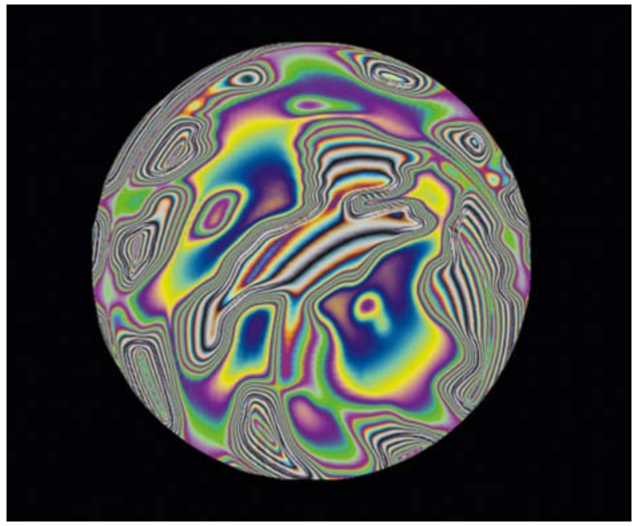

Fig. 1: The intensity of the reflected light which was obtained by multiple interference in a thin film with varying thickness. A white RGB source was applied.

sensor in a camera, with the best possible image of a self-emitting or illuminated object. In non-imaging optics, the light source is to be tailored in order to perform a specific task, e.g. the headlight of a car or the generation of a femtosecond pulse for eye surgery. Optics and photonics have benefited from various essential advances in technology in recent decades. These include the development of numerous new light sources like lasers, laser diodes and LEDs. Although optics is often understood as dealing with the visible region of the electromagnetic spectrum (only 390–700 nm), nowadays optics and photonics deal with much shorter (1 nm and below) and longer (1–10 µm) wavelengths as well. In the early time of optics, components were mainly restricted to planar and spherical surfaces, but nowadays we talk about freeform surfaces with aspherical, and even more general, height profiles. Optics profit from the development of lithography for electronics, which has brought about the fields of micro- and nano-optics where surfaces are structured on a nanometer scale in order to achieve specific optical functions through the surface, or even in the volume of a bulk medium. The combination of optics with modern computer technology makes adaptive-optics concepts and detector technologies which were completely unthinkable one decade ago possible.

The new chances for innovative developments through optics and photonics have unleashed a creative demand for manipulating and controlling light in every imaginable way. The development of such innovative products requires expert tools to model and to design the optical devices in order to be able to combine the light sources, components and detectors in a way which enables the demanded function. The development of modern photonics systems cannot be done in an experimental way, but must be based on simulation technology and digital twins. For more than 2000 years, optical modeling has mainly relied on ray optics, which is often also referred to as geometrical optics. This is possible because it can be shown that the modeling and design of lens systems for imaging can, in most cases, be fully based on ray optics. However, with the development of new sources and components and the ever increasing demand for non-imaging optical functions, optical modeling and design must be based on physical optics, sometimes also referred to as wave optics, in order to provide simulation technologies which are accurate enough and which give access to all those parameters of light which are of concern for the application.

Physical optics is based on Maxwell's equations, a system of differential equations. Though mathematicians have provided powerful solvers for those equations, in optics such universal Maxwell solvers, e.g. the Finite Element Method (FEM),

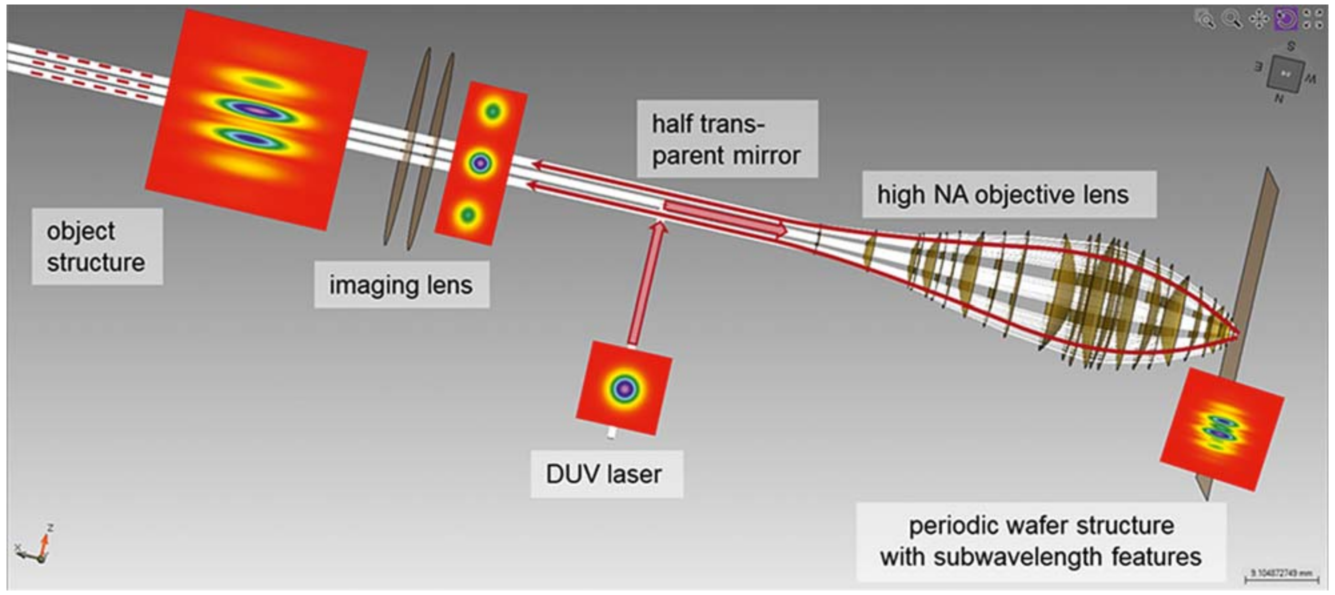

Fig. 2: Example of a complex optical setup (high-NA wafer inspection system) which often requires the application of efficient optimization tools to identify the optimum of merit functions defined by numerous different system parameters.

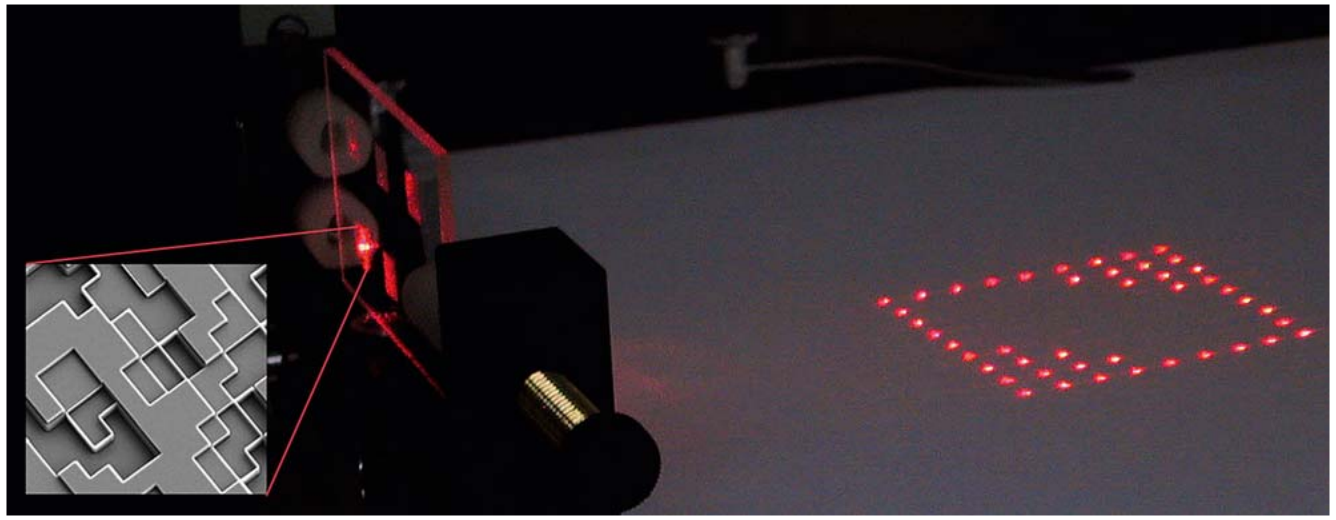

Fig. 3: Illustration of a diffractive beam splitter designed using VirtualLab and manufactured by the Institute of Applied Physics at the Friedrich Schiller University Jena – Germany

are not practical for tackling system modeling because of excessive computation time and use of computer resources. However, they are very important for modeling nano-optical devices, also as part of larger optical systems. Because of the practical limitations of these universal Maxwell solvers, ray tracing still dominates simulation technology in optics. Thus, the demand for a fast physical optics modeling concept has recently gained momentum. Prof. Frank Wyrowski and his teams at the Applied Computational Optics group at the Friedrich-Schiller-University of Jena and the companies LightTrans and Wyrowski Photonics have developed the concept of optical field tracing to provide a fast Maxwell solver which facilitates the usage of physical optics to model and design optical systems. In field tracing, different regions of a system are modeled with different specialized techniques in order to obtain a fast physical optics solution. When needed, that includes, for instance, FEM, but restricted to the smallest possible region of the system: for example the scattering sample in the modeling of a microscope. The optics software VirtualLab Fusion is based on field tracing to provide physical optics modeling and design, but includes ray tracing as well. In its second-generation field-tracing technology, which will be released in 2017, the fast physical optics concepts will be released to the public, precipitating the beginning of a breakthrough in optical modeling and design software.

The ability of fast physical optics modeling must be combined with solid concepts for the design of optical systems to perform the required optical function and to provide a system which can be fabricated with low variation of the output parameters at the same time. The design requires the optimization of the free parameters in the system, which can range from a few to hundreds and even thousands, and the analysis of the robustness of the designed system. Therefore, the Robust Design Optimization software optiSLang is the perfect companion for the optics software VirtualLab Fusion. The combination of both tools enables a fast and reliable design of optical systems, design understanding, multi-objective optimization and robustness analysis in a fully automated manner. Furthermore, it is possible to perform a Robust Design Optimization: a coupled optimization and robustness analysis to obtain a design that is optimal and robust in terms of input tolerances at the same time. In order to enable optiSLang to realize its full power for metamodeling in optics, VirtualLab Fusion can work in a batch mode under control of optiSLang. The input parameters are defined in a dialogue in VirtualLab Fusion and the output parameters are registered by the detectors that the optical design user has defined. Both types of parameters are automatically recognized by optiSLang and a wizard is provided to set up the whole workflow using the respective files that can be exported from VirtualLab in a convenient manner. Once the workflow is established, all available analyses can be performed.

As mentioned before, optics and photonics is a technical enabler. Thus, it is always embedded in larger systems. This requires, at some stage of the Technology Readiness Level (TRL), the combination of the optical modeling with mechanical and thermomechanical modeling, e.g. with ANSYS. When the lenses of an optical system are mounted or are exposed to a thermal source, a mechanical deformation will take place that can influence the optical performance dramatically. To understand and quantify that influence, the coupling of both domains, optics and thermomechanics, is a very important but also very new and challenging field of application. There has been no software solution available that allows this coupling with VirtualLab. optiSLang acts here as an integration and automation tool to establish complex workflows with several CAx tools in order to overcome this limitation.

In the following, we want to show the combination of VirtualLab and optiSLang to enable the optimization of a diffractive beam splitter (DBS) which divides an incident laser beam into several separated laser beams using a diffractive optical element (DOE) as illustrated in Fig. 3. Important applications for such a DBS are the generation of reference patterns for motion

tracking (like Microsoft Kinect [1]) and 3D surface measurements [2], as well as the parallelization and speed increase of laser material processing [3].

The optimization of such periodic DBS microstructures is challenging if large diffraction angles need to be realized. This kind of high-numerical-aperture (NA) DBSs must have microstructured features in the order of the wavelength of light. This requires a fully vectorial and rigorous analysis of the light interaction with the microstructure, which is beyond the scope of the typically applied thin-element approximation (TEA) [4]. For example, the high-NA DBS given in Fig. 4 will be optimized by a combination of VirtualLab's Fourier Modal Method [5] (which is a rigorous and fully vectorial solver of Maxwell's equations) and optiSLang.

As optimization target, the total diffraction efficiency η

$$\eta = \eta_1 + \eta_{-1} + \eta_3 + \eta_{-3} + \eta_5 + \eta_{-5}$$

should be maximized and the uniformity error U should be

$$U = \frac{\eta_{\max} - \eta_{\min}}{\eta_{\max} + \eta_{\min}} < 0.5\%$$

Here, η_i with $i \in \{-5;-3;-1;+1;+3;+5\}$ represent the diffraction order efficiencies of the 6 beams to be generated by the DBS. In addition, due to fabrication constraints, the smallest feature size of the microstructure should be larger than 300nm. The free parameters which should be optimized by the parametric optimization are the lengths of the 6 intervals (L1-L6) within one DBS structure period given in Fig. 5. Furthermore, the scaling of the modulation depth (z-Scaling) is a free parameter. An initial design result was obtained by VirtualLab's Iterative Fourier Transformation Algorithm. In the following, this design should be further improved performing, at first, a sensitivity analysis, followed by a parametric optimization.

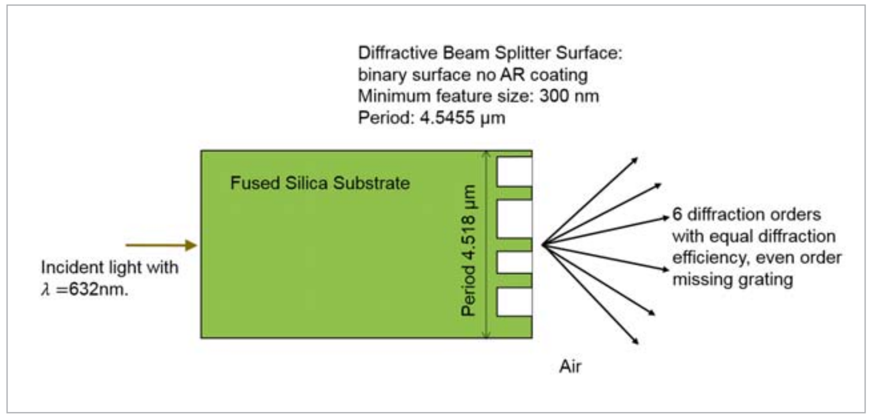

Fig.4: High-NA DBS setup dividing one incident beam into 6 beams with the same diffraction efficiency. This setup will be optimized in the following by a combination of VirtualLab Fusion and optiSLang.

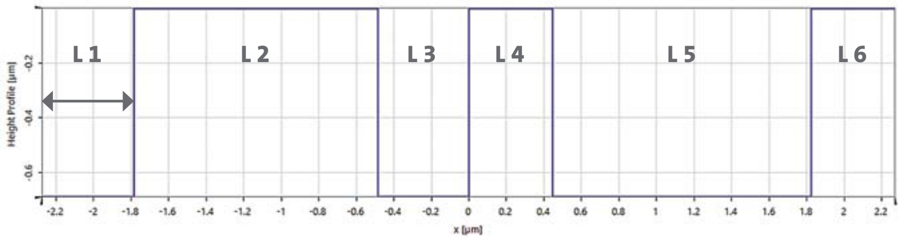

Fig. 5: Cross-section along a single period of the DBS microstructure. The structure is parametrized by the width of the six intervals. In addition, there is a free height scaling factor to adjust the profile height.

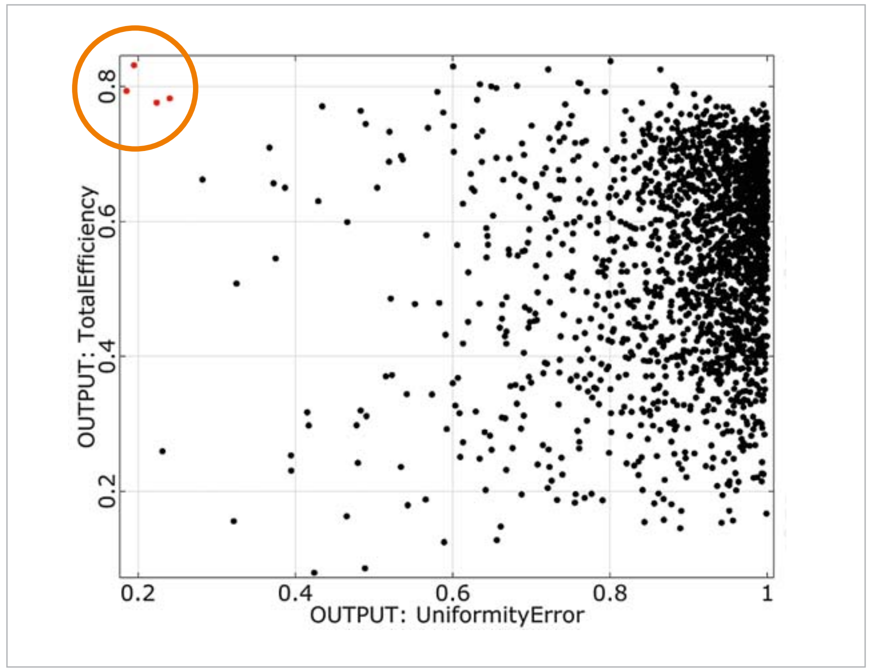

Fig. 6: Results I of the sensitivity analysis performed by optiSLang. The objective is in a small subspace: only 4 out of 2000 samples are close to the optimum.

In a first step, a sensitivity analysis is done in optiSLang to identify the optimization potential by estimation of the variation of response. This sensitivity analysis also helps to understand and verify dependencies between input and response variations using metamodels. An advanced Latin hypercube sampling was used to scan the parameter space using 2000 different DBS designs. The performance of these 2000 designs is shown in Fig. 6.

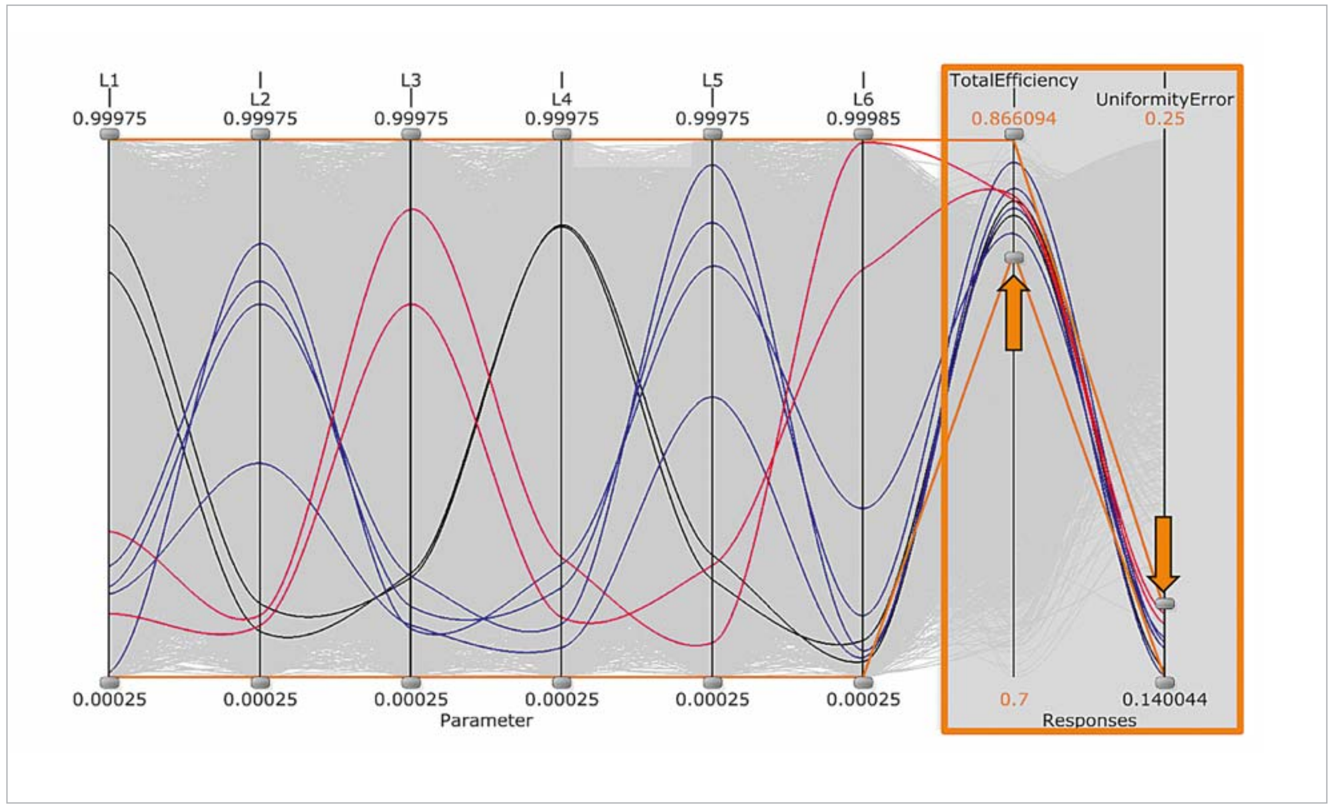

Fig. 7: Results II of the sensitivity analysis performed by optiSLang. Corresponding widths L1/L4, L2/L5 and L3/L6

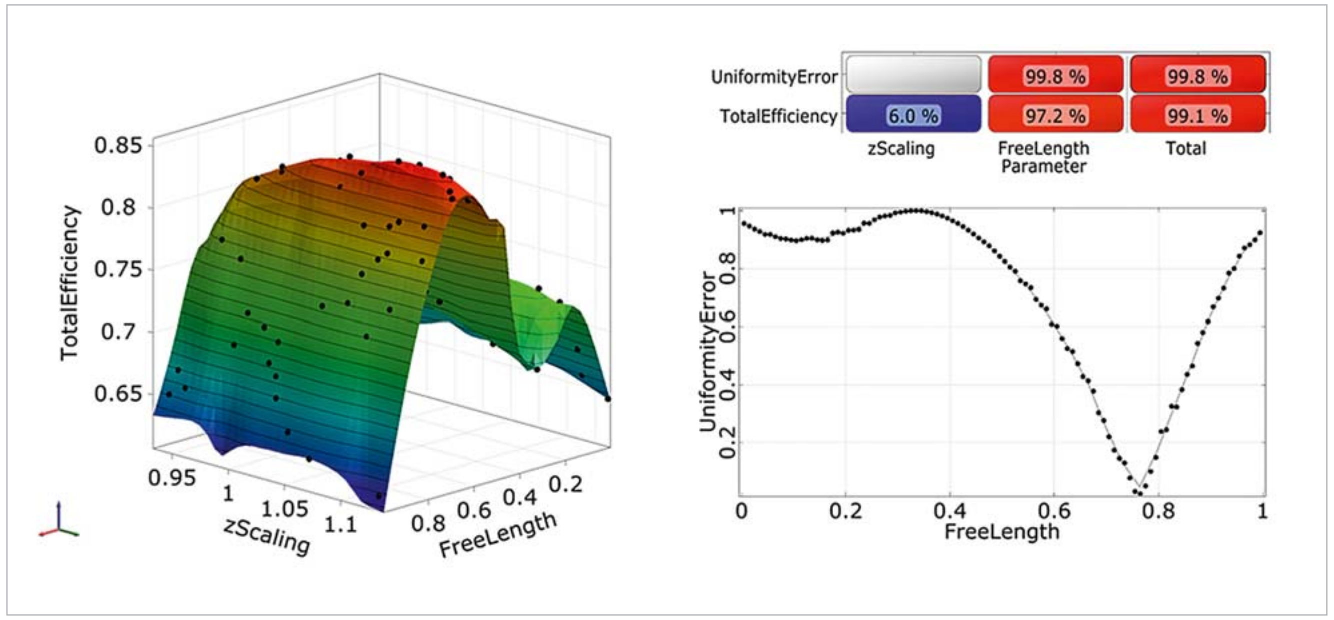

Fig. 8: Results III of the sensitivity analysis performed by optiSLang. A metamodel is found describing the response of the design (COP>99%). All responses depend strongly on the FreeLength parameter. The Uniformity Error is independent of z-Scaling within the chosen parameter range.

Designs exist where both objectives are not, or are only slightly, in conflict. Consequently, the definition in one objective function or with uniformity error U as a constraint will be most efficient. The parallel coordinate plot given in Fig. 7, which is another result of the sensitivity analysis, indicates that for designs close to the optimum (U < 25%, > 70 %), the lengths L1/L4, L2/L5 and L3/L6 correspond to each other.

Consequently, we can assume L2=L5 and L1=L3=L4=L6 (due to the periodicity of the microstructure). Thus, we can reduce the number of free parameters describing the widths of the intervals to a single free parameter, which is called FreeLength in the following. As shown in Fig. 8, the newly introduced FreeLength parameter has significant influence in the DBS performance. The z-Scaling parameter has just a minor influence.

Title Story // Optics & Photonics

After reducing the complexity of the optimization problem from 7 to 2 free parameters, a parametric optimization based on the Adaptive Response Surface Method (ARSM) by optiSLang is performed. The optimization results are shown in Fig. 9. The uniformity error could especially be reduced significantly.

	Target Design	Initial IFTA Design	Rigorous Design
Total Efficiency	maximize	80,9 %	81,4 %
Uniformity Error	<= 0,5 %	6,4 %	0,498 %

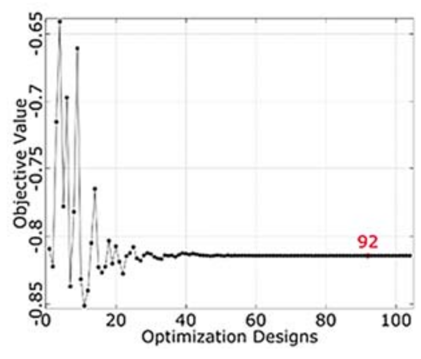

Fig. 9: Rigorous parametric optimization of DBS using optiSLang's ARSM. The uniformity error could especially be significantly lowered by the rigorous parametric optimization design.

It is evident that optics and photonics have a vital role to play in the current framework of technological innovation, both in its own right and as an enabler for other fields. The ever more stringent requirements increasingly imposed on optical systems in order to realize the ever more imaginative applications coming into vogue can no longer be met satisfactorily with bare-bones ray tracing: there is, consequently, a tendency towards simulation paradigms able to incorporate the full physical-optics picture within realistic constraints of simulation time and computation requirements. And this is precisely the answer that VirtualLab Fusion provides with its second-generation field-tracing approach.

But technological and scientific innovation seldom takes place within the closed confines of a single subject matter: bringing together expertise from different fields is what, throughout history, has tended to yield the best results. This is the backdrop for the collaboration between VirtualLab Fusion and optiSLang. Combining the paradigm-shifting field-tracing concept of VirtualLab Fusion with the cutting-edge optimization skills of optiSLang will open the door to a new level in the realm of optical system design.

Authors //
Roberto Knoth, Stefan Steiner, Christian Hellmann, Olga Baladron-Zorita (LightTrans International UG) / Frank Wyrowski (Friedrich Schiller University Jena)

Source // www.dynardo.de/en/library

Refrences //

1. Du, Pei-Qin, SHIH, Hsi-Fu, CHEN, Jenq-Shyong y WANG, Yi-Shiang. "Design and verification of diffractive optical elements for speckle generation of 3-D range sensors". Optical Review. 2016, vol 23, 6, p. 1017–1025.
2. Chan, Shih-Yu, Hsi-Fu Shih, Jenq-Shyong Chen. "Depth measurement using structured light and spatial frequency". Appl. Opt. 2016, vol 55, 19, p. 5069–5075.
3. Taghizadeh, M.R., P. Blair, K. Ballüder, A.J. Waddie, P. Rudman, N. Ross. "Design and fabrication of diffractive elements for laser material processing applications". Optics and Lasers in Engineering. 2000, vol 34, 4–6, p. 289 - 307.
4. Wyrowski, F. & Kuhn, M. (2011), "Introduction to field tracing", Journal of Modern Optics 58(5-6), p. 449-466.
5. Li, Lifeng. Mathematical Reflections on the Fourier Modal Method in Grating Theory. Philadelphia, PA, USA: Society for Industrial and Applied Mathematics, 2001, p. 111–139.