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RESEARCH PAPER

Potential of E-beam lithography for micro- and nano-optics fabrication on large areas

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ABSTRACT. The availability of high-resolution and high-throughput lithographic fabrication technologies, such as electron-beam lithography, based on variable shaped beam writing and character projection opens the way for the flexible use of various optical nano-structures for some of the most demanding applications. We discuss the technical features, advantages, and limitations of these pattering approaches and show how they can favorably be combined to realize optical nano-structures for applications, which are as diverse as gratings for ultra-short laser pulses or high-resolution spectrometers, computer generated holograms for asphere testing, various optical meta-structures (lenses and gratings), or UV-polarizers.

Keywords: electron-beam lithography; optical micro- and nano-structures; gratings; computer-generated holograms; optical meta-structures

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1 Introduction

Micro-structured optics experienced a first peak in the mid-1990s, when numerous attempts to realize optical functions based on diffractive structures were made.[1] However, at that time, diffractive optics were not able to fulfill many of the high-flying expectations. Nevertheless, since then, substantial improvements of the fabrication technologies specifically dedicated to the realization of optical micro- and nano-structures have brought such elements into a multitude of applications.[2–7] A particularly topical area of research in this context is the field of optical meta-materials as they offer access to novel optical functionalities by nano-patterning.[8]

This paper is focused on the huge potential of modern electron-beam lithography methods for the realization of the required nano-structures for flexibly tailoring optical functions in high-end applications. The related challenge is twofold: the micro-structured optical elements require a precise control of characteristic feature sizes on the nanometer scale and at the same time elements with application relevant sizes need to be patterned. Electron-beam lithography based on the variable shaped beam (VSB) writing principle, in which expanded geometrical primitives such as rectangles or triangles of flexible size can be exposed with a single shot, is a first step toward this direction. For highly repetitive patterns, such as parts of gratings, the use of a so-called character projection (CP) can be even more advantageous. Compared with pixel-based exposure strategies, an enormous reduction in shots and writing time of about 100…10,000 can be achieved with this approach.[9]

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In the following, the basics of the different writing regimes in electron-beam lithography are briefly reviewed. Their advantages and limitations are discussed afterward by selected examples of optical micro-structures. A particular emphasis is given to the potential of patterning elements, such as meta-lenses and meta-gratings with dimensions of up to 300 mm, as well as the impact of the used writing regime on critical optical performance parameters, such as light scattering or wave-front quality.

2 Efficient E-Beam Lithography for Nano-Optical Structures

Tailoring the propagation of light in optical applications can physically be accomplished either by refraction or reflection of light at interfaces of different materials or by coherent (or incoherent) scattering processes at structures having dimensions comparable to the light's wavelength and making use of diffraction phenomena. The latter approach has become accessible to optical applications with the development of specific direct write lithographic patterning methods in the 1980s and 1990s and has become even more popular in recent years due to substantial improvements of computer-aided optical modeling and design techniques, particularly for a class of structures referred to as optical meta-materials. These meta-structures consist of patterns with lateral dimensions even smaller than the wavelength of the used light. Their tailorable light–structure interaction gives access to optical functionalities that cannot be achieved by conventional optical materials, such as a customizable wavelength-dependent diffraction,[4] polarization dependent behavior,[10] specific absorption properties,[11] and even improved non-linear optical responses, e.g., for wavelength conversion.

The realization of optical nano-structures poses several challenges to the used patterning technology. In addition to a high resolution, a large flexibility for reproducibly generating various lateral geometries with high positional accuracy is needed. To be able to address real-world applications, the used technology also needs to be able to achieve this on large areas within a reasonable pattering duration and—specific to optical applications—on flexible substrate geometries and materials. This combination of requirements clearly distinguishes lithography for optical nano-structures from that used in the field of micro-electronics. In micro-optics, the initial pattern definition by a lithographic exposure of a resist layer is typically followed by subsequent etching or lift-off processes to transfer the pattern into layers of specific material or the underlying substrate. A very common patterning process for the realization of binary micro-optical elements, which is also used in the labs of the Fraunhofer Institute of Applied Optics and Precision Engineering (Fraunhofer IOF), is shown in Fig. 1.

The patterning process starts by depositing a double layer of chromium (Cr) and electron beam sensitive resist on the substrate. Afterward, the grating structure is exposed into the resist by electron beam lithography using a SB350 OS e-beam writer (Vistec Electron Beam GmbH). A dry-etching process is used to transfer the pattern into the chromium layer. After removal of the remaining resist, the Cr-layer then acts as a hard-mask for a subsequent reactive ion etching step in an inductively coupled plasma reactor (ICP-etching) for transferring the grating structure into

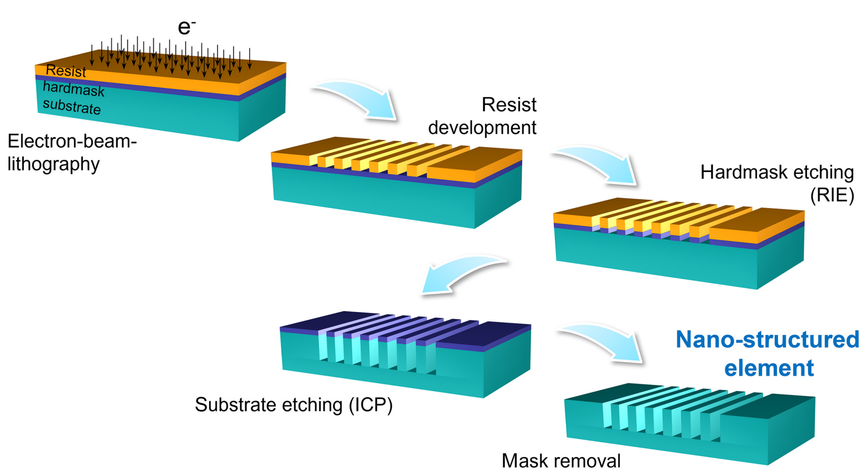

Fig. 1 Manufacturing process flow for the lithographic realization of optical nano-structures in a fused silica substrate.

the required high aspect-ratio structure in the surface of the fused-silica substrate. Finally, the remaining chromium mask-layer is removed. The resulting fused-silica structure can either be used directly as an optical element or utilized as a master for subsequent replication steps, such as a nano-imprint process for the realization of a larger number of components.

The advantage of using an e-beam writer for the definition of the nano-structures is the achievable high lateral resolution in the range of a few nanometers related to the high electron energy. However, in e-beam lithography tools using a focused spot-beam probe, the writing speed and thus the throughput are rather low, restricting the patternable area to a few square millimeters only. A substantial increase of writing speed by several orders of magnitude can be achieved with the so-called VSB technology and the cell projection (CP) writing regime. Both use a different kind of electron optics for generating an electron probe of flexible size or even projecting more complex cells, respectively. The different e-beam writing regimes are schematically explained in Fig. 2.

In the VSB regime, the pattern to be exposed is decomposed into primitives (rectangles and triangles) of variable sizes with a maximum dimension of about 2 μm $\times$ 2 μm. Their actual size can be adjusted in 1 nm steps. The single exposure shots are stitched together with high accuracy to form more complex exposure geometries [e.g., curvilinear pattern of computer-generated holograms (CGH), see Sec. 3].

In the case of small (and potentially repetitive) complex exposure geometries, the approximation of the desired shapes by the rectangular or triangular imposes a substantial amount of exposure shots and, consequently, a long exposure time, which can be of unrealistic extent. In addition to the related cost of such an exposure, the stability of the overall process becomes a challenge.[12] The way toward an even higher throughput in such a situation is the use of the CP writing mode, in which a complex exposure geometry is hard coded in a so-called mini-reticle. In the case of the SB350 OS e-beam writer, a complex pattern with a maximum 2 μm $\times$ 2 μm size can be exposed with a single-electron beam shot. The electron optics allows for a selection of various geometries (depending on their actual size between 2048 and 12,800 mini-reticles). They can be flexibly combined with each other in an exposure layout and seamlessly combined with VSB shots. Examples of CP written pattern are shown in Fig. 3.

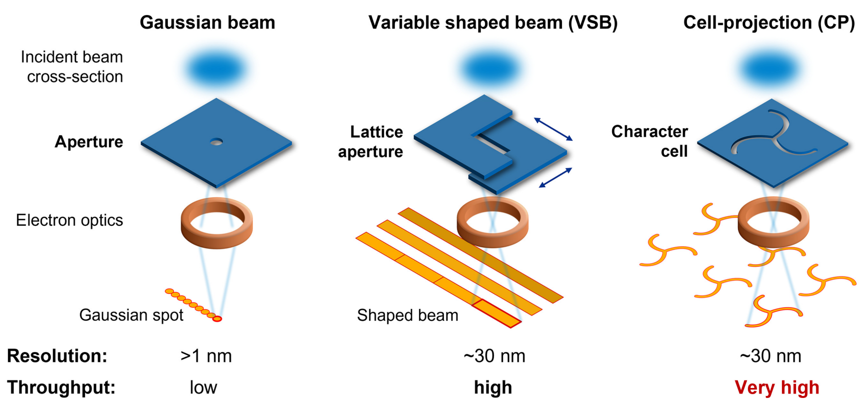

Fig. 2 Writing regimes in e-beam lithography.

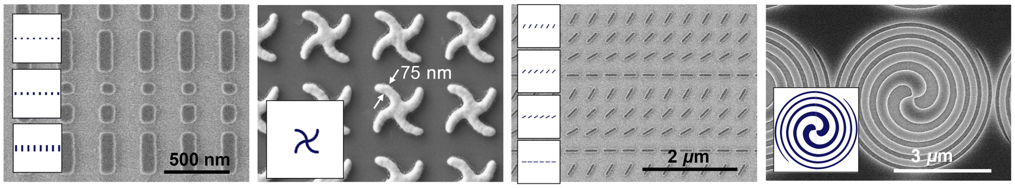

Fig. 3 SEM-images of complex patterns generated by e-beam lithography with the CP writing regime. The insets are showing the shapes of the mini-reticles that were used to compose the shown pattern.

3 Examples of e-Beam Written Nano-Optical Elements

The potential of the different e-beam writing regimes is discussed in the following by three different examples: a large high-precision CGH for testing of aspherical mirrors, a very large metagrating, and a diffractive axicon with very low light scattering. Other examples of e-beam written optical micro-structures, such as various high-performance gratings for space-borne spectroscopy or ground-based astronomical instruments, have been reported in other publications.[4,7]

3.1 Computer-Generated Holograms for Asphere Testing of Telescope Optics

State-of-the-art astronomical telescopes typically require aspheric or freeform mirrors or lenses to achieve their desired diffraction limited performance. The method of choice for characterizing such optics with highest precision is interferometric testing utilizing CGH to adapt the wavefront of the interferometer to the aspherical shape of the surface under test. This way, the CGH becomes the ruler for the accuracy of the optical element and consequently needs to obey extreme accuracy requirements with respect to the generated wavefront. In modern telescopes, rms wave-front error values in the single nanometer range need to be achieved. The fabrication process of the CGH is similar to the one shown in Fig. 1, and the wave-front error requirement directly translates into a positioning accuracy requirement for the lithographic exposure process.

An example of extreme requirements on the accuracy of the test CGH is the secondary mirror of ESO's Extremely Large Telescope.[13] Due to its convex shape, the 4.2 m diameter secondary mirror could not be directly characterized using a CGH but is tested during the fabrication process using a refractive aspheric reference plate. The CGH for the characterization of this reference plate was fabricated by Fraunhofer IOF using the e-beam lithographic processes as described above. Optically, a CGH can be considered to be a grating structure with a locally varying grating period. The corresponding patterns are not repetitive and were exposed using the VSB writing mode on a 9 in. fused-silica mask-blank substrate. To minimize WFE contributions from the substrate itself, it was polished using an ion-beam figuring process to a residual transmitted WFE of 2.4 nm rms.

Figure 4 shows the measurement setup for the interferometric testing of the reference plate and the manufactured test CGH. Due to the use of the VSB writing mode, it was possible to pattern the CGH area of about 205 mm × 205 mm within an exposure time of about 54.6 h.

Local positioning errors ε of the lithographic writing process of the CGH structure directly translate into a wavefront error ΔW of the CGH according to

$$\Delta W(x, y) = -m\lambda \frac{\varepsilon(x, y)}{P(x, y)}, \tag{1}$$

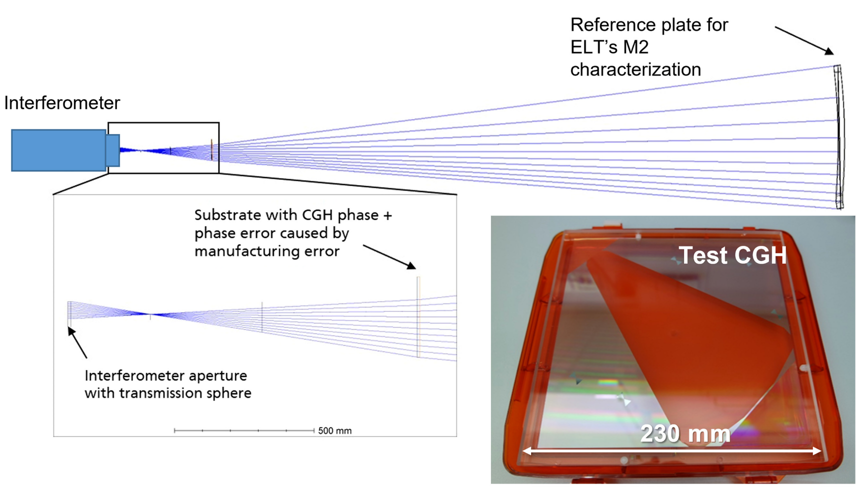

Fig. 4 Interferometric measurement setup for the ELT's M2 reference plate utilizing a high-precision CGH of 230 mm × 230 mm size for adaptation of the spherical wavefront exiting the interferometer to the aspheric surface shape of the reference plate.

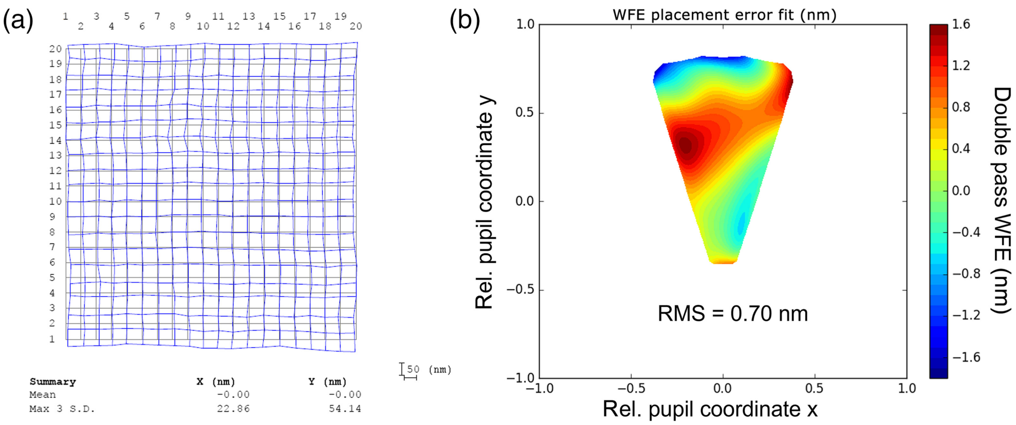

Fig. 5 (a) Lateral placement error of the e-beam exposure of the CGH for the ELT M2 reference plate measured with the LMS-IPRO. (b) Resulting wave-front error map in double-pass transmission caused by the placement error.

where $P(x, y)$ is the local period of the CGH. The positioning error of the exposure was characterized with an LMS-IPRO 2 (KLA Tencor) by utilizing a grid of 20×20 fiducial marks. The obtained placement error amounts to 7.6 and 18.1 nm in the x and y directions, respectively [see Fig. 5(a)]. The corresponding WFE in double-pass transmission caused by this placement error is shown in Fig. 5(b) and amounts to 0.7 nm rms only, which shows the high accuracy achievable with the e-beam lithographic pattern definition.

3.2 Meta-Grating of Extreme Dimension

In the second example, the huge potential of the CP writing mode to cover very large areas of optical nano-structures is demonstrated. This is of particular interest for the realization of meta-structures as they often are composed of a set of repeated unit cells. The fabrication of such structures using electron beam lithography is quite usual due to the high resolution provided by this lithography method. However, typically the reported attempts use electron optics with a spot beam probe, restricting the realizable optical areas to a few square millimeters only.[14]

Here we report the realization of nano-imprint master of an effective medium meta-grating on a full 300 mm diameter silicon wafer. The layout of the grating, as shown in Fig. 6, is composed of dense arrays of dots with varying diameters and pitches. The smallest feature size is 100 nm with a pitch of 200 nm. The sheer number of dots in this pattern prohibits a realization using the VSB writing mode, even if the circular pattern would not be approximated with multiple rectangular exposure shots. Figure 6(b) shows how the meta-structure was assembled out of a set of mini-reticles, each of which contains an array of 6×6 up to 12×12 circular exposure shapes being exposed in a single shot.

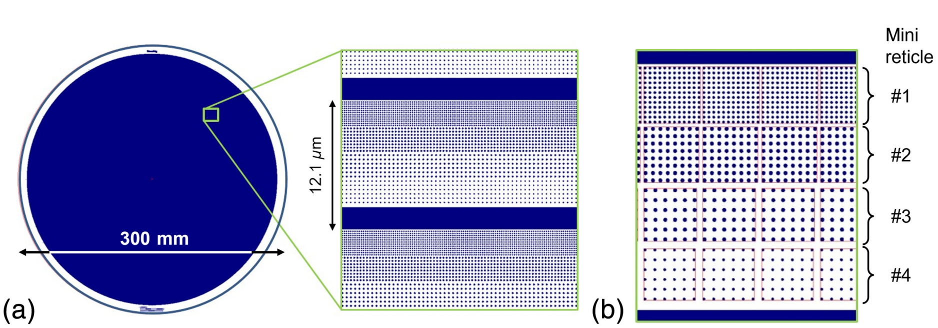

Fig. 6 (a) Layout of the meta-grating on a 300 mm Si-wafer. (b) Decomposition of the grating period into a set of four different mini-reticles, each containing an array of 6×6 up to 12×12 circular dots of varying sizes and pitches.

Table 1 Simulated and experimentally determined writing times and shot count for the realization of the meta-grating with VSB- and CP-writing modes, respectively.

Exposure mode	VSB	CP
Shot count	6×10^{11}	1×10^{10}
Write time (simulated)	74 days 20 h	1 day 12 h
Write time (experimental)	—	1 day 12 h

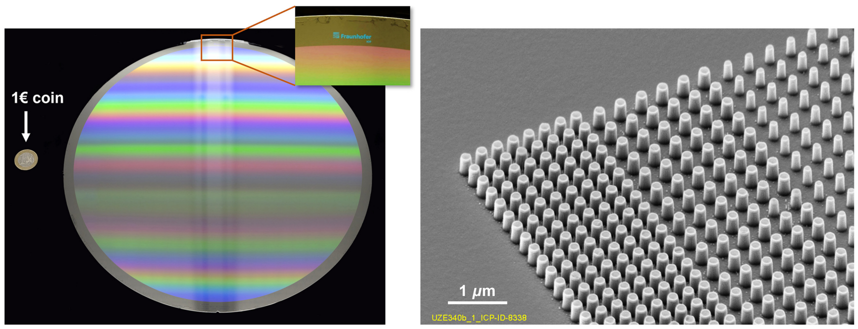

Fig. 7 Photograph of the 280 mm diameter meta-grating on a 300 mm Si-wafer and SEM-images of the resist structure and the meta-structure after etching transfer into the Si-substrate.

The comparison of the simulated write time estimations for the VSB and CP approaches are shown in Table 1 together with the measured write time for the CP-based realization of the demonstrator.

Figure 7 shows the results of the real exposure and pattern transfer into an Si-wafer by reactive ion etching. This meta-grating is dedicated to being used as a master in a subsequent nano-imprint replication, which is currently under development for such large areas and small feature sizes. Currently, the shown CP-based electron beam lithography process seems to be the only feasible technology for realizing such large meta-structures within a reasonable time frame.

3.3 Low Scattering Diffractive Axicon Structure

The third example demonstrates the potential of the CP writing mode for improving the optical function of micro-optical elements, namely the reduction of deterministic straylight, particularly in curvilinear structures as they occur in CGHs. The exposure of such structures using the common VSB approach requires the approximation of curved grating lines of variable local periodicity by rectangular or triangular e-beam shots. As the local periodicity or the curve's orientation changes only weakly with the local position on the layout of the structure, a kind of Moiré-pattern between the desired structure and its shot approximation can occur. This can result in macroscopic super-structures overlayed to the desired diffractive structure, which is visible to the naked eye. In combination with the preferential direction of the rectangular exposure shapes, these super-structures lead to undesired diffraction effects or "diffraction ghosts," which can affect the wave-front accuracy of the interferometric measurement (in the case of asphere test-CGHs) or the spectroscopic sensitivity (in the case of high-resolution spectrometer gratings). The CP writing mode in e-beam lithography can efficiently be used to suppress such super-structures and the related undesired diffraction effect. To demonstrate this, a diffractive axicon structure was chosen as a test structure and was exposed with both approaches, the VSB- and CP-writing modes, respectively. A diffractive axicon consists of a circular grating structure and can thus be considered the special case of a CGH with a local constant periodicity but circularly varying grating orientation. It is chosen for this example as its optical characterization with respect to the occurring light scattering pattern is more intuitive than for a more general test-CGH.

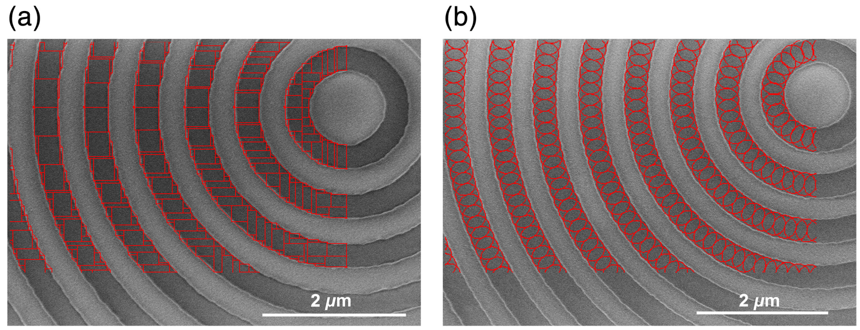

Fig. 8 SEM-images of the binary axicon structure exposed with (a) the VSB writing mode and (b) the CP writing mode. Overlaid on the SEM images are the used exposure shots.

The axicon structure was defined with a local period of 700 nm and a diameter of the single element of 15 mm. It was exposed with both writing modes on an Si-wafer into a chemically amplified resist of type FEP171 (Fujifilm). In the case of the conventional VSB exposure, the exposure data preparation utilizes the available rectangular and triangular shapes to obtain the best possible structure approximation. In the case of the CP writing mode, the exposure data only contain circular exposure shots with a diameter that was chosen out of the several hundreds of available mini-reticles to best fit to the desired line-width of the axicon. Figure 8 shows SEM-images of the resulting binary resist structure in the center of the axicons after development. Overlayed to the SEM-images are the exposure shapes used in the two writing modes. It can be seen that, on the microscopic scale, both exposures lead to very similar results without obvious differences in line-edge roughness or pattern fidelity.

If the two different structures are analyzed with respect to their optical functionality and particularly to their light scattering pattern and diffraction ghosts, a clear difference becomes obvious, as shown in Fig. 9. The light scattering measurements at a wavelength of $\lambda = 395$ nm were directly performed on the resist structures using the scatterometer MLS10 developed at Fraunhofer IOF.[15] No additional transfer processes were applied to obtain the scattering footprint of the writing process only and avoid additional effects from such subsequent process steps.

The desired optical function of the axicon is the generation of a circular diffraction ring, which is clearly shown in the measurements. However, in addition to this diffraction pattern, in particular, the VSB written element shows various additional features in the recorded scattering pattern arising from the decomposition of the circular grating into the rectangular and triangular exposure shots. This includes spurious partial ring patterns visible outside the desired diffraction ring as well as cross-like diffraction structures along the cartesian coordinate directions. In the case of the CP written axicon, these undesired patterns are clearly suppressed or not even present. Thus the realization of the optical function is much cleaner, and a negative impact on the wave-front accuracy or signal-to-noise ratio in an application of such elements can be substantially reduced.

Furthermore, the writing time for the axicon element using the CP writing mode is about a factor 2 shorter than the approach using the VSB mode.

4 Comparison to Other Lithographic Techniques

In this section, we briefly discuss the presented technique of VSB/CP e-beam writing in comparison with two other contemporary high-resolution lithographic patterning approaches: multi-beam e-beam lithography, also known as complementary electron beam lithography (CEBL),[16] and optical lithography.

Today's optical lithography tools are basically well able to address the feature-sizes of the elements presented in the previous section. The exposure in those tools is based on a demagnified imaging of a pattern containing photomask. With this parallel approach, optical lithography is always much faster than any direct-write technique. The central question for making a choice between optical lithography or VSB/CP-based e-beam lithography is, therefore, the effort needed

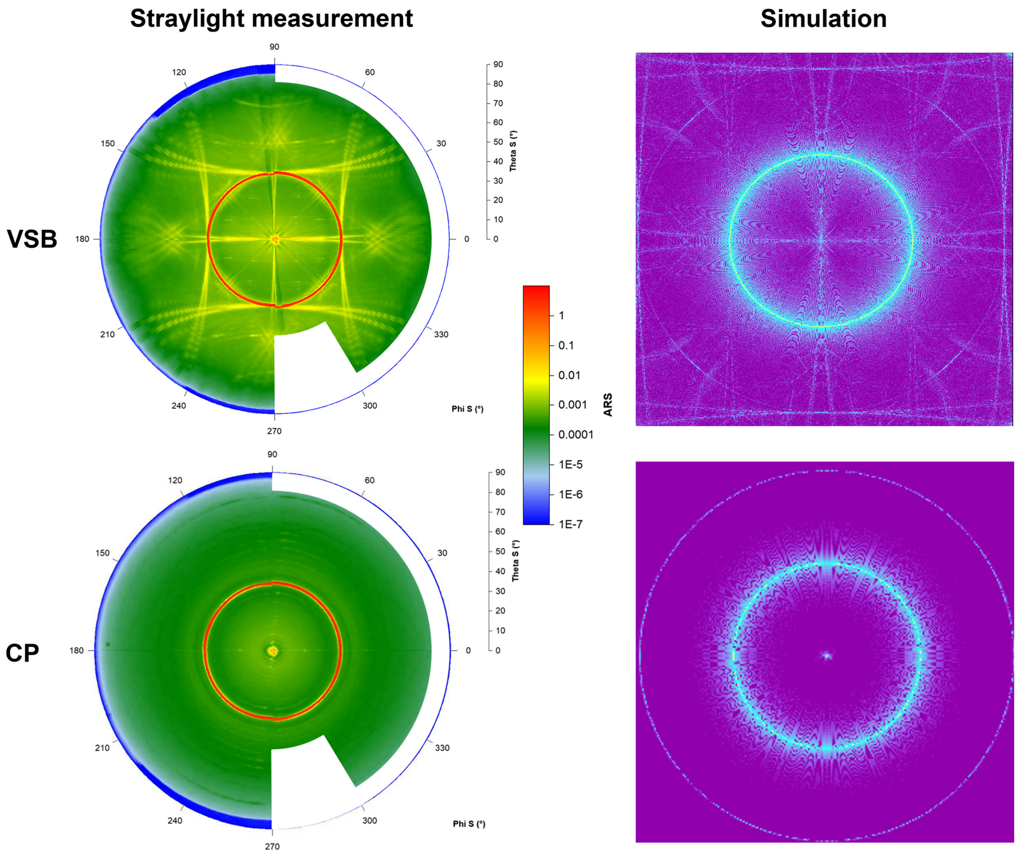

Fig. 9 Straylight measurements taken in the backward hemisphere at a wavelength of 395 nm of the exposed axicon structures. The upper and lower rows show the measurements for VSB and CP writing modes, respectively. On the right side, the comparison with a calculated diffraction pattern based on the shot approximations for both cases is presented.

to achieve the required optical performance. For the optical lithography, this is related to the quality of the mask. A high-resolution optical pattern may require a very fine approximation of the mask pattern, leading to large writing times in a mask shop and thus to considerable costs. Consequently, the choice between the different techniques must include considerations on the number of elements required and the price for which the final consumer product can be sold. This cannot be generalized. A favorable deployment scenario for VSB/CP e-beam lithography can always be found in cases of prototyping and design optimization of high-resolution structures as well as for small series productions in which the fabrication of a dedicated high-end photomask is simply not economical. Here VSB/CP-based e-beam lithography offers a high flexibility and short turn-around time in combination with a reasonable cost figure. This also includes a higher flexibility with respect to the usable substrate dimensions and materials, which are often much more restricted in optical lithography approaches.

The multibeam e-beam direct write approach or CEBL, on the other hand, can outperform the discussed VSB/CP-technique with respect to the achievable writing speed. Also, the patterning flexibility is not restricted; thus the CEBL can basically address similar applications as described in Sec. 3. The writing time scales with the number of the available beams. A conventional 6-in. photomask can be exposed in about 10 h, almost independently of the shot count or the complexity of the pattern.[17] The use of a Gaussian beam shape allows for the exposure of a high-resolution curvilinear pattern. On the other hand, the CEBL technique has greater challenges to achieving a homogeneous positioning accuracy and CD-control and substantially higher demands on data processing. As a result, currently the tool cost for a CEBL-writer exceeds the one of a VSB/CP-tool; therefore, the cost-of-ownership is higher. Thus the decision between either of the techniques has to be made based on detailed considerations of the addressed application scenarios.

5 Summary

Electron beam lithography based on modern writing regimes, such as the VSB principle or the CP mode, combine the advantages of a very high patterning resolution, high positioning accuracy, and high pattern fidelity with a high-throughput superseding the writing speed of focused point beam probes by several orders of magnitude. In particular, for the realization of nano-optical structures that often contain repetitive patterns, this is an extremely powerful lithography technique capable of addressing application relevant element sizes of several 100 cm^2 dimension. The implementation of a mini-reticle stage for the CP exposure mode carrying several thousands of different shapes assures the highest flexibility for the realization of complex layouts. Furthermore, both writing modes can favorably be combined to realize optical nano-structures for applications that are as diverse as gratings for ultra-short laser pulses or high-resolution spectrometers, computer generated holograms for asphere testing, optical meta-lenses, UV-polarizers with locally variant orientation, and various others.

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