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An integrated exposure and measurement tool for 5-DOF direct laser writing

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Abstract. Accurate and uniform fabrication of microstructures on highly curved substrates requires exposure with the waist of a focused laser beam at every point. In order to realize this, the exposure beam must be held perpendicular and focused onto the local substrate. Here we present an optical tool for our developed 5-axis nano-positioning and nano-measurement machine based on the chromatic differential confocal microscope.

1 Introduction

Flexible prototyping of microstructures via direct laser writing (DLW) or laserablation recently enabled a whole new field for the creation of MEMS and metamaterials. Thereby a single laser spot exposes or ablates a small volume of photoresist on a substrate. Using multiphoton absorption in DLW, this even allowed for the creation of extended complex three-dimensional structures [1]. The fabrication on, and modification of, highly curved substrates such as lenses, mirrors or free-form objects however remains an open challenge. Accurate structuring of such substrates could enhance the manufacturing of hybrid diffractive-refractive optical elements, highly integrated systems such as wearables or fully-3D chip designs.

In order to achieve highest accuracy at the current point of structuring on the substrate (POS), the optical tool needs to follow local surface slope as indicated by the tilted objective in figure 1. A current project at our institute is the metrological 5-axis nano-positioning and nano-measuring machine (NPMM-5D) [2], also shown in fig. 1, that allows to position and rotate around the POS with nanometer-accuracy by following the extended Abbe-principle. For the rotations, this is achieved via the measurement of three distances by Fabry-Pérot interferometers towards a reference hemispherical mirror. This limits the available space for toolheads and therefore requires innovative miniaturized measurement and structuring systems.

2 Designed integrated tool

Here we present the design of a fiber-coupled toolhead that integrates a differential confocal surface probe with an exposure laser via a common fiber. A schematic overview of the system is shown in figure 2. The differential confocal surface probe is composed of two red probe beams that, using axial chromatic aberration, are focused into two separated focal planes. Via signal processing as indicated by fig. 2, a normalized differential signal (FES) between these two planes is created. It will be used to keep the POS at a desired working point between these two planes. Furthermore, the current slope of the substrate can be determined via the autocollimation principle and an integrated small CMOS chip.

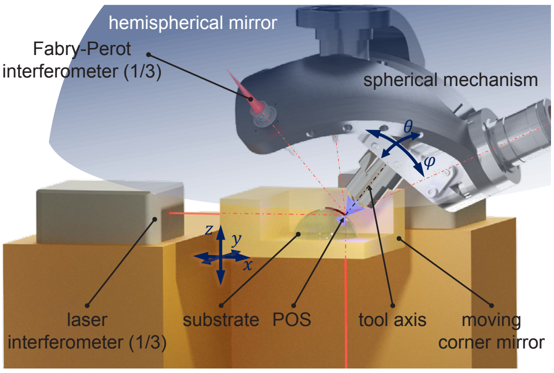

Figure 1. CAD model view of the significant parts of the NPMM-5D.

A difficulty arises from the demands of the photoresist. It is required that the measurement probe beam is not exposing the resist, while the blue exposure beam is turned off. To prevent this, the probe beam shall use a red wavelength as indicated in fig. 2. For simple refractive elements, the aforementioned chromatic aberration now has the negative side-effect that the focal plane of the exposure beam and the probe beams would be separated too far [3]. To overcome this, we developed an optical system based on simple stock optics that is achromatic for the blue exposure beam and the center wavelength $\bar{\lambda} = 652\,\mathrm{nm}$ of the probe beams, but also offers sufficient chromatic aberration for the two probe beams to be separated far enough for the creation of the differential confocal signal. To simplify the design process, commonly a paraxial estimation is undertaken [4].

The difference of the optical power between two wavelength F and C of a sequential arrangement of k thin lenses $\Delta\Phi_{1,k}$ might be expressed paraxially as:

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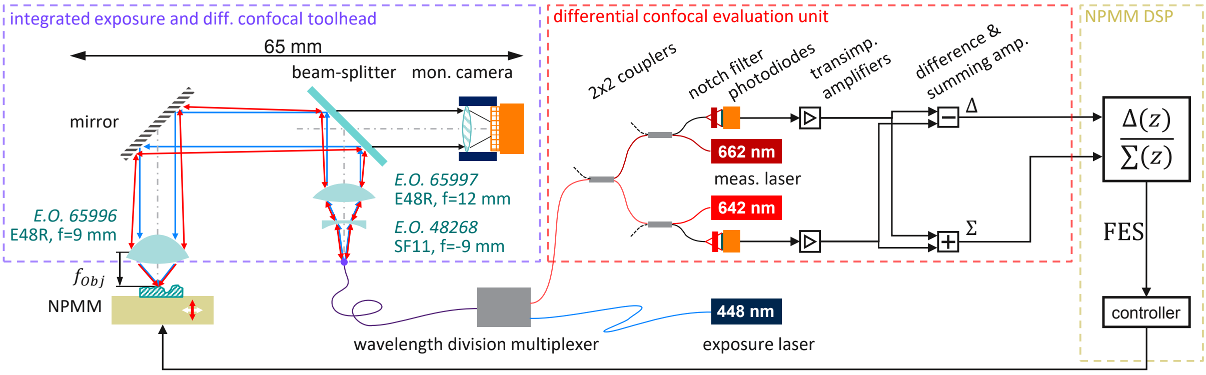

Figure 2. Schematic of designed optical measurement and exposure tool.

$$\Delta\Phi^{FC}_{1,k} = \frac{\Phi^d_k}{\nu_k} + \sum_{i=1}^{k-1}\left(\Phi^d_i \frac{\nu_i - p_i + 1}{\nu_i} \prod_{j=i+1}^{k}\left(1 - (s_j - k_{j-1,1})\Phi^d_j \frac{\nu_j - p_j + 1}{\nu_j}\right) - \Phi^d_i \frac{\nu_i - p_i}{\nu_i} \prod_{j=i+1}^{k}\left(1 - (s_j - k_{j-1,1})\Phi^d_j \frac{\nu_j - p_j}{\nu_j}\right)\right) \tag{1}$$

Where ν and p are the to the task adjusted ABBE-number and partial dispersion towards the design wavelength d of the individual lens. s_i are the axial distances between the thin lenses and and $k_{i,1}$ is the axial distance of the subsystem from the first to the kth lens towards its last lens.

With this eq. 1 and an analogue term for the secondary spectrum $\Delta\Phi^{dC}_{1,k}$ the chromatic demands can be fulfilled by the minimization of $\Delta\Phi^{FC}_{1,k}$ and maximization $\Delta\Phi^{dC}_{1,k}$. However, during the investigation we found that this estimation may lead to the wrong impression that a system of only positive lenses can become achromatic. This stems from the omitted thickness of the lenses. It is desirable to maintain the simplicity of the problem for initial optical designs. Therefore, we suggest the following criterion ϵ to determine the trustworthiness of the paraxial estimation of $\Delta\Phi^{FC}_{1,k}$:

$$\epsilon = \sum_{i=1}^{k} \frac{1\text{mm}}{f_i} \cdot \frac{p_i}{\nu_i} \quad , k \geq 2 \tag{2}$$

Where f_i is the focal length of the individual lens at the design wavelength. Keeping $-10^{-3} < \epsilon < 0$ ensures, that there is enough negative refractive power to create achromatism with refractive elements. Following this methodology a suitable initial system could easily be identified before the axial distances where additionally optimized in Zemax.

3 Results

The adjusted system was characterized by the axial scan of a plane mirror through the three focii. Figure 3 shows on the left the three axial response curves measured on the fiber-coupled photodetectors. The highest peak corresponds to the waist of the focused beams. As per design, the blue response from the exposure laser is in between the two red probe beams. The resulting norm. differential signal (FES) is shown in fig. 3 (right) and exhibits an approximately 6 µm wide steep linear slope. A fitted linear function reveals a very high axial sensitivity of $S_z = 721.2\,\text{pm/dig} \pm 0.4\,\text{pm/dig}\ (95\%)$. This allows for a sensitive detection of a defocused exposure laser.

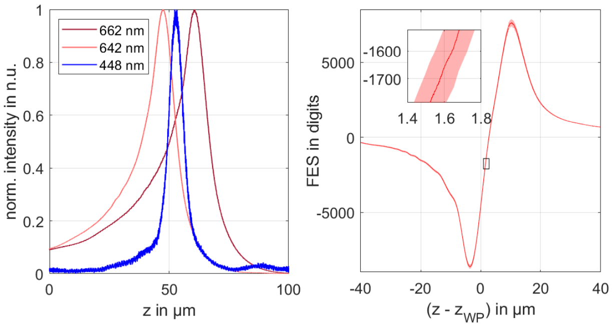

Figure 3. Measured axial response curves (left) and FES (right).

Averaging 100 axial measurements over 45 min resulted in an axial uncertainty of 72.3 nm. The asymmetric shapes of the two probe beam depth responses as shown in fig. 3 reduce the linearity. It is further amplified by a too high axial separation of the focii of the two probe beams. Besides other geometrical inaccuracies, this is caused by the adjustment of the output power of the probe beams to be identical. The different currents in the laserdiodes significantly shift the output wavelength.

4 Conclusion

We presented our newly designed tool for DLW on highly curved structures with the NPMM-5D. A design methodology for the integration of a chromatic differential confocal probe with an exposure beam path was briefly introduced. With its demonstrated nanometer depth sensitivity, the waist of the exposure beam can be kept on the surface of the substrate. This enables the production of uniform nanostructures. Furthermore, the optical toolhead integrates the possibility for the measurement of the surface slope angle which shall be investigated in near future.

References

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