Adaptive optics for direct laser writing with plasma emission aberration sensing

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Abstract: Aberrations affect the focal spot quality in direct laser write applications when focusing through a refractive index mismatch. Closed loop adaptive optics can correct these aberrations if a suitable feedback signal can be found. Focusing an ultrafast laser beam into transparent dielectric material can lead to plasma formation in the focal region. We report using the supercontinuum emitted by such a plasma to measure the optical aberrations, the subsequent aberration correction using a spatial light modulator and the fabrication of nanostructures using the corrected optical system.

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References and links

Laser material processing with short pulsed laser beams has been widely used for the fabrication of devices such as artificial bandgap materials [1], microfluidic devices [2, 3], metal nanostructures [4, 5, 6] and photonic devices based upon embedded waveguides [7]. Structures are created by focusing the laser into the material where multiphoton absorption and/or avalanche effects cause permanent material changes in the focal region [8, 9]. The fidelity of fabrication depends strongly on the quality of the focal spot. In many cases, the quality of the focus is impaired by aberrations. A common problem is a mismatch between the refractive indices of the processed material and the objective immersion medium. For example, nanophotonic devices are often fabricated in glasses that are not index matched with the focusing objective. While the aberration function caused by such a mismatch can be modelled, other effects caused by non-linearity or birefringence are much harder to derive. It is therefore desirable to have a means of measuring aberrations directly. In contrast to microscopy, where they can be deduced from acquired images [10], alternative ways are required in nanofabrication applications, where the substrates are usually homogeneous and featureless. In recent publications it has been demonstrated that spatial characteristics of the fabricated structures can be used to estimate aberrations [11, 12]. We propose an alternative way of measuring aberrations, which is based upon the supercontinuum emission of a plasma created in the beam focus. The plasma, which is generated by multiphoton absorption and avalanche effects, can usually be observed during nanofabrication processes and does not necessarily indicate the destruction of the glass matrix. Under strong focusing conditions, the plasma emission is mostly isotropic and unpolarized [13]. We show that an unaberrated focal spot corresponds to maximal plasma emission and demonstrate the correction of system and sample-induced aberrations using a spatial light modulator (SLM).

Figure 1 shows a sketch of the experimental set-up. The pulses emitted from the regeneratively amplified titanium sapphire laser (Solstice, Newport/Spectra Physics, 100 fs pulse duration, 1 kHz repetition rate, 790 nm centre wavelength) were attenuated using a rotatable half wave plate and a Glan-Taylor polarizer. A neutral density filter was inserted if very low powers were required. The expanded beam was directed to a reflective liquid crystal SLM (X10468-02, Hamamatsu Photonics), which was used to shape the laser wavefront. The SLM was imaged onto the objective pupil. The specimen was located on a 3D piezo stage (Tritor102SG, Piezosystem Jena) which provided up to 100 µm translation in all axes. The system incorporated a LED illuminated transmission microscope for observing the specimen. This microscope was also used to measure the intensity of the plasma emission from the laser focus. A figure inset shows the sample plane as it appeared on the CCD. The bright spot is the light emitted by the plasma; the line below had been “written” into the specimen (borosilicate glass) by moving the sam-
ple slowly whilst the laser was on. The laser exposure had changed the refractive index of the material. This was visible in the transmission microscope under slightly defocused imaging.

To verify that an unaberrated focus corresponds to the most intense plasma emission, the laser wavefront was deliberately distorted with the SLM and the corresponding plasma emission quantified. We represented the wavefront $\Phi$ within the objective pupil as a series of Zernike modes: $\Phi(\rho, \theta) = \sum_i a_i Z_i(\rho, \theta)$ with $a_i$ being the Zernike coefficients and $Z_i$ the modes, using the single index numbering scheme explained by Neil et al. [14]. The normalized radial and angular coordinates are denoted by $\rho$ and $\theta$, respectively. Four different Zernike modes (astigmatism, coma, trefoil, tetrafoil) were subsequently applied to the wavefront and the beam was focused into lead glass (SF57, $n = 1.825$). The plasma emission intensity was measured using the CCD camera. The objective was an Olympus PlanApo (60 x 1.4 NA, oil immersion) and the pulse energy was 0.01 $\mu$J. The results are summarized in Fig. 2. The graph shows the dependence of the plasma emission intensity on the applied rms aberration amplitude. The same aberration modes were applied in magnitudes from -0.8 to 0.8 rad with a step size of 0.4 rad. At each step, a defect was created by 100 laser pulses, each of 0.1 $\mu$J energy. The images on the right are widefield images of the created defects, imaged with the fabrication objective. For all tested modes, the most isotropic defects corresponded to the maximal plasma emission. These results show that the plasma emission intensity is a valid metric for the focal spot quality.

Aberrations were corrected on a mode by mode basis using an iterative procedure [15]. Bias aberrations $\pm b_i Z_i$ were introduced by the SLM and the corresponding plasma emission intensities $I_{\pm}$ measured by integrating over the corresponding region on the CCD (see Fig. 1(b)). A phase update $\Delta \Phi_i = -g (I_{+,i} - I_{-,i}) Z_i$ was then added to the SLM diffraction pattern and the whole process repeated until the aberration had been compensated, i.e. $I_{+,i} - I_{-,i} = 0$. The gain factor $g$ was experimentally determined for fast convergence. To expedite the process, both bias aberrations were simultaneously applied by displaying a binary pattern of the form

$$\Phi(\rho, \theta) = \begin{cases} 0 & \text{if } \text{mod}_{2\pi}(k\rho \cos \theta + b_i Z_i) < \pi \\ \pi & \text{otherwise} \end{cases}$$

(1)

where mod$_{2\pi}$ symbolizes the “modulo-” operation that restricts the phase to an interval of $[0, 2\pi]$. Equation (1) represents a binarized blazed grating with superimposed Zernike bias. A representative pattern is shown in Fig. 1(b). The grating constant $k$ was chosen such that both diffraction orders were separated by about 5 $\mu$m in the specimen plane. As a consequence of using a binary phase pattern, the phases of the orders are naturally conjugated, i.e. one is distorted by $+b_i Z_i$ and the other by $-b_i Z_i$. Similar binary patterns have been previously used.
to measure aberrations in light transmitted through a lithium niobate substrate [16]. Using the plasma emission, the time required to correct one mode was typically in the range of a few seconds. In order to keep the plasma-induced material change as small as possible during the aberration sensing, the pulse energies were set to a level where they just generated sufficient plasma emission for detection on the CCD. We found that accurate measurements require the specimen to be moved during the process. Low speeds of around 1-2 μm/s were sufficient.

To verify the aberration correction process, we introduced a known wavefront distortion using the SLM and measured it by using the plasma signal and the procedure explained above. The applied aberration magnitude of 1 rad rms was randomly distributed over seven low order Zernike modes. The modal coefficients are represented by the blue bar plot of Fig. 3(a). The remaining aberration magnitude after subsequent correction cycles is shown in Fig. 3(b). Each cycle involved measuring aberrations in the corresponding seven Zernike modes. Correction was complete to an accuracy of little more than 0.1 rad after two cycles. After three cycles, there remained a residual error of around 0.05 rad (≪λ/100), which shows the accuracy limit of the method. The red bars in Fig. 3(a) show the Zernike coefficients obtained after six cycles.

Finally, the spherical aberration caused by a refractive index mismatch of objective immersion medium and sample was measured and corrected. The aberration function can be expressed

![Graph: Plasma emission intensity when different aberrations are applied using the SLM. Images: Defects created in the bulk of lead glass, with aberrations applied from -0.8 rad to 0.8 rad (rms value). For each mode, the most isotropic defect shape corresponds to the maximal plasma emission. The side length of each image corresponds to 5 μm.](chart1.png)

![Graph: Remaining phase aberration after subsequent correction cycles.](chart2.png)
as [17, 18]

$$\Phi_{SA}(\rho) = -\frac{2\pi}{\lambda_0} d_{\text{nom}} NA \left[ \left( \frac{n_2^2}{NA^2} - \rho^2 \right)^{\frac{1}{2}} - \left( \frac{n_1^2}{NA^2} - \rho^2 \right)^{\frac{1}{2}} \right]. \quad (2)$$

Here, $\lambda_0$ denotes the vacuum wavelength, $NA$ the numerical aperture of the microscope objective and $d_{\text{nom}}$ the nominal focusing depth as indicated in Fig. 1. $n_1$ and $n_2$ are the refractive indices of immersion medium and substrate, respectively. The spherical aberration $\Phi_{SA}$ causes not only an elongation, but also an axial translation of the focal spot. As this translation is easily removed by refocusing the stage, it is reasonable to define a modified function $\hat{\Phi}_{SA}$, where the defocus has been removed to minimize the rms amplitude. Such a function will be easier to shape with adaptive optical elements.

The defocus function is defined as:

$$S(\rho) = \frac{1}{N} \left[ (1 - \rho^2 NA^2/n_2^2)^{\frac{1}{2}} - M \right]. \quad (3)$$

Here, $M$ is defined to remove the piston offset and $N$ represents a normalization factor, such that the rms value of $S$ is one:

$$M = \frac{1}{8\pi} \left[ \left( n_1^2/NA^3 \right) \arcsin \left( NA/n_1 \right) - \left( n_1^2/NA^2 - 2 \right) \left( 1 - NA^2/n_1^2 \right) \right], \quad (4)$$

$$N = \left[ \frac{1}{15\pi} \left( 5 - 3NA^2/n_1^2 \right) \right]^{\frac{1}{2}}. \quad (5)$$

Spherical aberration was measured using the binary pattern of Eq. (1), with $Z_i$ replaced by $\hat{\Phi}_{SA}$.

To test our aberration correction procedure in a common nanofabrication set-up, we corrected for system and depth induced aberrations in fused silica using an air objective (Leitz 50× 0.85 NA, no coverslip correction). Figure 4 shows widefield transmission (a) and reflection confocal (b) images of defects, which have been produced by single laser pulses ($E=3 \mu J$). For imaging, the fused silica block was turned by 90 degrees. The confocal images were taken at a wavelength of 405nm with the Olympus objective (1.4 NA, oil immersion) and appropriate aberration correction. Each row of images corresponds to a different focusing depth. The defects shown on the left were produced without any aberration correction. Clearly the quality, i.e. the local confinement of the defects, degrades quickly with increasing fabrication depth. At a nominal focus depth of 80 $\mu$m (corresponding to 130 $\mu$m fabrication depth) the affected region extends more than 30 $\mu$m in the axial direction. The white marks in the widefield images denote the respective axial positions of defects when aberration correction was applied. The defects shown in the right column have been fabricated using corrective phase patterns obtained by our aberration sensing technique. The resulting defect shapes are essentially independent of the focusing depth. At a nominal focus depth of 80 $\mu$m, we were able to produce defects extending as little as 1.5 $\mu$m in axial direction using a significantly lower laser pulse energy of 0.05 $\mu$J (see Fig.4(c)). Without application of the corrective SLM pattern, at this pulse energy the focal intensity was below the threshold of visible material modification. At a depth of 80 $\mu$m and when using the 50× 0.85 NA objective, the rms amplitude of the correction pattern $\hat{\Phi}$ was 2.6 rad. Similar rms magnitudes with comparable peak to valley values have to be corrected when focusing 700 $\mu$m (nominal depth) deep into fused silica with an air lens of 0.45 NA. This much larger depth is due to the strong dependence of spherical aberration on the objective NA. It is therefore possible to fabricate aberration corrected nanostructures at large depths with low NA objectives, which are commonly used for writing waveguide based photonic devices.
The presented results introduce the plasma emission intensity as a suitable metric for measuring aberrations in nanofabrication applications. We have shown that the absence of aberrations corresponds to a maximum in the emission intensity and successfully applied the correction procedure to fused silica and lead glass. Although not described here we have also tested the technique with optical media spanning a wide range of refractive indices, namely borosilicate glass ($n = 1.52$ coverslips, Menzel Gläser) and diamond ($n = 2.42$). We expect the method to be applicable to a variety of other materials. We described a way of measuring aberrations using binary diffraction patterns and investigated the suitability of a Zernike modal wavefront expansion. Accurate aberration compensation was achieved after three correction cycles. Finally, we demonstrated the measurement and compensation of spherical aberration, introduced by a strong refractive index mismatch between air and fused silica. With wavefront correction, aberration free defects in 130 μm physical depth have been fabricated without significant degradation in quality. Such mismatches between the lens immersion medium and the fabrication substrate exist quite often. Although oil immersion lenses can sometimes be used for certain types of glass, they cannot eliminate aberrations for all materials (e.g. SF57). Also, in some situations the use of an immersion medium is incompatible with the fabrication system. Adaptive aberration correction is essential in these cases.

The presented results comprise only cases where the laser propagated almost parallel to the optical axis through the entire optical system. However, the method can also be applied in situations where the laser is obliquely coupled into the objective. In such cases, the method will also account for additional field dependent aberrations.

The method could be directly applied to the fabrication of photonic devices which are based upon embedded waveguides. Three dimensional structures can be fabricated with consistent quality up to large depths by using correction patterns which have been obtained in proceeding measurements. Aberration correction should also lead to improved quality of waveguide Bragg gratings [19]. Their functionality crucially depends on their refractive index contrast, which is strongly affected by aberrations in the writing beam.

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