Aberration correction in laser micro-fabrication

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Direct laser writing with an ultrafast beam is becoming a useful tool in the fabrication of a range of three dimensional micrometer scale structures [1]. The technique involves focusing the output of a femtosecond laser with a relatively high numerical aperture (NA>0.5) objective lens into the bulk of a suitable transparent substrate. The band gap is typically several times higher than the incident photon energy. Therefore any absorption is highly nonlinear and only occurs near the focus where the intensity is maximum. Furthermore, the ultrashort nature of the pulse minimizes heat diffusion and any material modification is highly localized at the focus, without any damage to the surface. The confinement of the structural change to the focal volume enables the precise machining of complex structures in three dimensions. Promising applications include the manufacture of waveguides [2], artificial bandgap materials [3], and metallic nanostructures [4].

Since there is a direct correlation between fabricated features and the focal intensity distribution, fine control over the focal spot is often desired, as is the elimination of any optical aberrations. A common problem arises when focusing into a specimen with a different refractive index to that of the immersion medium of the objective lens.

In particular, there exists a depth-dependent spherical aberration related to the refraction of rays at the specimen interface [5], whereby marginal and axial rays of the focussing cone converge to different axial positions, as demonstrated in figure 1. The spherical aberration leads to a loss of resolution and power efficiency in fabrication, and these losses increase with focussing depth. The aberration is particularly pronounced when high numerical aperture (NA) optics are employed and the refractive index mismatch is large. There is a characteristic elongation of the focal intensity distribution, leading to severe problems in creating fine features in the axial direction. One way of reducing this spherical aberration is to use an objective lens immersed in a suitable liquid, such as oil, that has a refractive index close to that of the substrate. However, this is not always practical and at high NA even slight differences in refractive index can be significant.

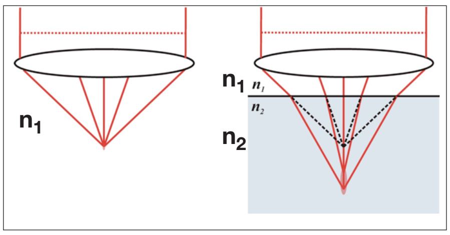

Figure 1: Illustration of spherical aberration caused by a refractive index mismatch: (left) aberration-free focusing; (right) refraction at the sample interface giving rise to the aberration

In order to restore diffraction limited resolution in the fabrication, an adaptive optical element (AOE) may be used to correct for depth dependent spherical aberration. The AOE is used before the focusing objective to impose a phase profile on a wavefront, which is equal and opposite to the aberration introduced by the refractive index mismatch at the sample surface. A typical AOE used in experiments would be a deformable mirror (DM), or liquid crystal spatial light modulator (SLM).

A major obstacle in using an AOE for the compensation of specimen-induced aberrations is determining the appropriate phase profile to impose on the wavefront. It is convenient to use a feedback metric from the fabrication process, such as the intensity of the continuum emission from the plasma generated at the fabrication focus. We have shown that optimising this plasma emission intensity through variation of the AOE minimizes the optical aberrations present and produces fabrication of the tightest features [6].

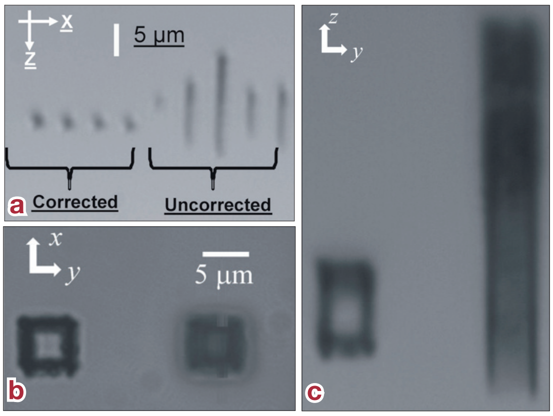

Figure 2: Fabrication of amorphous carbon defects 130 µm below the surface in diamond, with aberration compensation (left) and without (right). The fabrication laser beam is incident along the -z direction. In particular, (a) and (c) show the elongated focus caused by spherical aberration.

Fabrication with aberration correction

Vast improvements in fabrication are possible through aberration correction, especially when there is a large mismatch in refractive index (n) between the sample and immersion medium. Such is the case in diamond (n = 2.4), where spherical aberration is severe when using a 1.4NA oil immersion objective lens (n = 1.52).

Point defects in diamond

Figure 2 shows the results of fabrication of amorphous carbon point defects 130 µm below the surface in diamond. Without using an AOE, the point defects are elongated along the optical axis, as is expected for a feature that is heavily spherically aberrated. By employing an AOE (in this case a deformable mirror and spatial light modulator working in tandem), confined micron scale point defects can be generated and the power threshold drops by a factor greater than ten. The difference is even more pronounced when tracing the focus through the diamond in order to create continuous tracks of amorphous carbon. For example, drawing the outline of a cube is easily accomplished with aberration compensation, but impossible without the use of AOEs, as shown in Figure 2 (b) and (c).

Photonic crystals

Not surprisingly, the compensation of aberrations using adaptive optics in order to create fine structures is highly beneficial for the optical performance of photonic devices.

As an example of this, Figure 3 shows photonic crystals manufactured in lithium niobate by direct laser writing [7]. When viewed from above, it is difficult to discern the differences between the structures written with and without adaptive optics. However, when looking at the optical transmission the improvement in the reflection peak for the aberration compensated structure is clear.

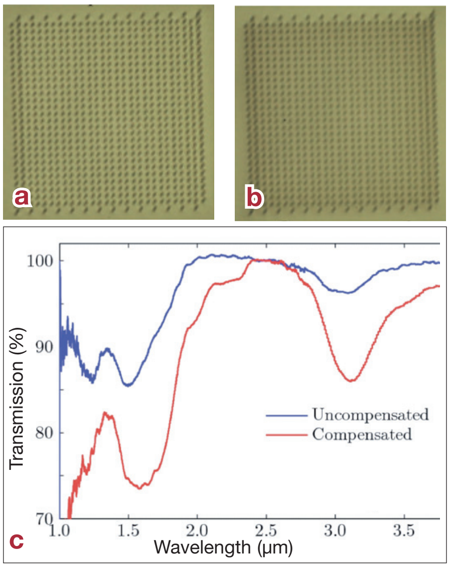

Figure 3: Fabrication of a photonic crystal in lithium niobate. Top: periodic structure viewed from above (a) without and (b) with aberration compensation. The benefits of aberration compensation are seen in the optical transmission of the photonic crystal in (c) below [7]

Parallel processing

The incorporation of an AOE, in particular an SLM, into a laser fabrication system is not only useful for aberration correction, but also allows for massive parallelization of the writing process. For example, computer generated holograms displayed on an SLM generate multiple fabrication foci simultaneously.

In the design of the hologram, attention must be given to the dispersion of the fabrication pulse. Due to the finite bandwidth (>10 nm) of a femtosecond pulse, there can be considerable chromatic aberration for light diffracted at large angles to the optical axis. Therefore it is expedient to create arrays of fabrication foci centred around the focus in a 3D block rather than a 2D plane. If points are spread in 3D, each requires a different amount of compensation for depth dependent spherical aberration [8], a consideration that must be included in the hologram design, as illustrated in Figure 4. As shown, the failure to compensate for spherical aberration separately at each point in the hologram design makes it impossible to fabricate the entire helix, even by increasing the incident power. However, when the spherical aberration compensation is included, all points in the structure are accurately fabricated simultaneously. The zero order spot is removed in these examples through generating an additional spot in the holographic array which is used to destructively interfere with the zero order.

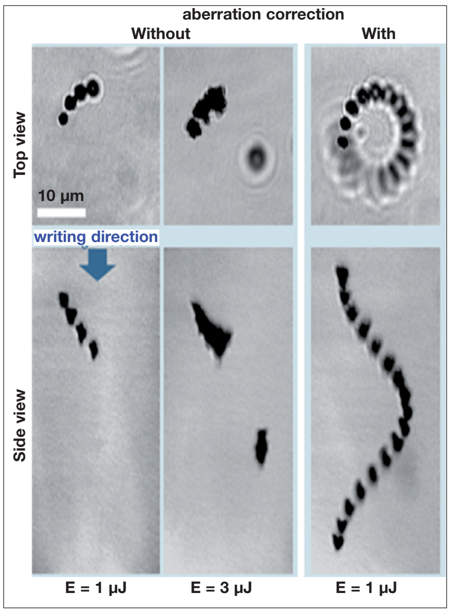

Figure 4: A 3D spiral of point defects simultaneously fabricated in diamond by a train of 50 laser pulses, each of energy E, using a single computer generated hologram [8]

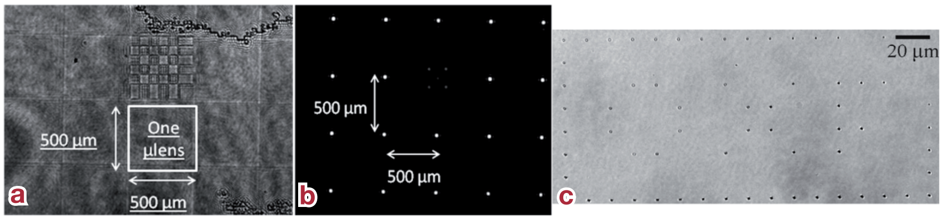

Figure 5: Multi-spot micro-machining using a SLM and micro-lens array. (a) Image showing the SLM mapped onto the micro-lens array; (b) Intensity distribution at the focus of the objective, where the focus of one microlens in the array has been deactivated for fabrication through spatially spreading the incident pulse energy; (c) fabricated array of voids on the surface of a fused silica slab, spelling OXF [9].

An alternative method for creating a large array of fabrication foci from a single laser beam is through the insertion of a micro-lens array. This method has the advantage that foci can be generated at a large distance from the optical axis without significant chromatic aberration. However, the resultant array of points is fixed and strictly periodic, offering little flexibility in the fabrication. It would be useful to address individual foci, which we have achieved by coupling a SLM to the lenslet array [9]. As can be seen in Figure 5, when the SLM is imaged onto the micro-lens array, a subset of pixels on the SLM corresponds to each lens. Applying suitable phase patterns to the SLM addresses the individual foci from the micro-lens array, allowing spots to be switched on and off for fabrication, equalized in intensity, steered and compensated for aberrations.

Another interesting application is emerging for adaptive optics in ultrafast laser inscription of waveguides. An SLM may be applied to beam shaping in the generation of photonic waveguiding structures of desired cross-section. An optical waveguide may be created by translating the specimen through the focus transverse to the optical axis. However, this leads to a correspondence between the focal shape and the waveguide cross-section.

A circular cross-section is desirable, but when an unshaped beam is focused into a glass substrate, the focal intensity distribution is several times larger in the axial direction than in the transverse, forming highly asymmetric guides. A SLM may be used for appropriate beam shaping, with the added advantage that the beam shaping may be adapted during fabrication to compensate for varying aberrations or to create embedded waveguides with smoothly changing properties.

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