Exploring the depth range for three-dimensional laser machining with aberration correction

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Abstract: The spherical aberration generated when focusing from air into another medium limits the depth at which ultrafast laser machining can be accurately maintained. We investigate how the depth range may be extended using aberration correction via a liquid crystal spatial light modulator (SLM), in both single point and parallel multi-point fabrication in fused silica. At a moderate numerical aperture (NA = 0.5), high fidelity fabrication with a significant level of parallelisation is demonstrated at the working distance of the objective lens, corresponding to a depth in the glass of 2.4 mm. With a higher numerical aperture (NA = 0.75) objective lens, single point fabrication is demonstrated to a depth of 1 mm utilising the full NA, and deeper with reduced NA, while maintaining high repeatability. We present a complementary theoretical model that enables prediction of the effectiveness of SLM based correction for different aberration magnitudes.

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References and links
32. E. Toratani, M. Kamata, and M. Obara, “Self-fabrication of void array in fused silica by femtosecond laser.”

References
34. L. Sudrie, A. Couairon, M. Franco, B. Lamouroux, B. Prade, S. Tzortzakis, and A. Mysyrowicz, “Femtosecond

1. Introduction

Ultrashort pulsed laser fabrication [1] in materials, such as glass or fused silica, is receiving increasing attention due to a range of interesting applications. The potential to generate accurately micron scale features in three dimensions has been previously used to great effect in waveguide circuits [2–6], microfluidic chips [7, 8], volume optics [9], welding [10] and the fabrication of microcomponents [11]. The key benefit of using ultrashort pulses for the fabrication is that the features generated can be highly localised in three dimensions. However, problems arise with 3D fabrication due to refraction of rays at the sample surface, giving rise to a depth dependent spherical aberration [12–14]. The magnitude of the aberration is strongly dependent on both the focusing depth and the numerical aperture (NA) of the focusing optic. Problems associated with the aberration may be circumvented by using a very low NA (0.1 - 0.2) objective [15] and sacrificing spatial resolution. Alternatively, an objective with higher NA and a correction collar may be used [16] which is effective within a range but often does not accommodate the full working distance and is not suitable for dynamic application. The focal distortion due to the aberration may actually be utilised in some applications, such as for the generation of an axial array of voids [17].

Adaptive optic elements, in particular liquid crystal spatial light modulators (SLMs), have become increasingly prevalent in recent years to counteract the effects of aberrations in laser fabrication. Implementations have included very high precision machining at high NA [18, 19], incorporation of aberration correction with parallelisation [20], longitudinal waveguide writing [21] and removal of aberrations induced near the sample edge [22]. Here, we explore both theoretically and experimentally the limits for aberration correction using a SLM when machining deep inside fused silica at different numerical apertures.

2. Focussing through a mismatch in refractive index

2.1. Spherical aberration and defocus phase functions

When light is focused from a medium with refractive index \(n_1\) into a sample with a differing refractive index \(n_2\), refraction of rays at the interface leads to an aberration of the focus. Typically the focal intensity distribution is both distorted and refocused, as demonstrated by Fig. 1(a). The effects are particularly pronounced for high numerical aperture (NA) objective lenses and/or when there is a large difference between the refractive index of the sample and that of the objective immersion medium. By considering the optical path length difference for rays as a function of their angular distribution exiting the objective [12], the phase in the pupil plane of the objective lens required to cancel the aberration induced by the interface is written as:

\[
\phi_{\text{SA}}(\rho) = \frac{-2\pi d_{\text{nom}}}{\lambda} \left( \sqrt{n_2^2 - (\text{NA} \rho)^2} - \sqrt{n_1^2 - (\text{NA} \rho)^2} \right) \tag{1}
\]

where \(\lambda\) is the wavelength of the light, \(\rho\) is the normalised pupil radius and \(d_{\text{nom}}\) is the nominal depth to which we are focusing within the sample. An example cut through such a phase distribution is presented in Fig. 1(b), for an example lens with NA=0.75, focusing from air \((n_1 = 1)\) into fused silica \((n_2 = 1.45\) at \(\lambda = 790\) nm) to a depth of \(d_{\text{nom}} = 100 \mu\text{m}\). The aberration contains a defocus element which leads to the depth of maximum intensity in the sample \(d_{\text{act}}\) being greater than the nominal focusing depth \(d_{\text{nom}}\). As this defocus is simply equivalent to a translation of the sample stage, it is standard practice to reduce the magnitude of the required SLM aberration correction by removing this component. The defocus-free spherical aberration
The defocus-free spherical aberration compensation function may be written as:

$$\hat{\phi}_{SA}(\rho) = \phi_{SA} - \frac{\langle \phi'_{SA}, D'_{n2} \rangle}{\langle D'_{n2}, D'_{n2} \rangle} D_{n2}$$  \hspace{1cm} (2)

where $D_{n2}$ is the phase required to defocus to a depth $d_{nom}$ in the sample medium. $\phi'_{SA}$ and $D'_{n2}$ correspond to the functions $\phi_{SA}$ and $D_{n2}$ following subtraction of their respective mean values, while $\langle \phi'_{SA}, D'_{n2} \rangle$ denotes an inner product between two functions defined as:

$$\langle X, Y \rangle = \int \int XY \rho d\rho d\theta$$  \hspace{1cm} (3)

where $\rho$ and $\theta$ represent normalised polar coordinates within the pupil. Since the analysis should be generally applicable to objective lenses with a high numerical aperture, it is important to employ a spherical, as opposed to a quadratic, form for the defocus phase [23]:

$$D_{n2}(\rho) = \frac{2 \pi d_{nom}}{\lambda} \sqrt{n_2^2 - (NA \rho)^2}$$  \hspace{1cm} (4)

Figure 1(c) displays the radial cut through the aberration phase from Fig. 1(b) with the defocus phase element removed as described in Eq. (2). The spherical aberration that leads to focal distortion is clearly apparent. The total phase range has dropped by a factor of ten following defocus removal, substantially reducing the demands on the adaptive optic element. Following the notation of Cumming et al. [24], we denote $1/s = 1 + \langle \phi'_{SA}, D'_{n2} \rangle / \langle D'_{n2}, D'_{n2} \rangle$ such that the defocus-free spherical aberration compensation function may be written as:

$$\hat{\phi}_{SA}(\rho) = \frac{2 \pi d_{nom}}{\lambda} \left(s \sqrt{n_2^2 - (NA \rho)^2} - \sqrt{n_2^2 - (NA \rho)^2} \right)$$  \hspace{1cm} (5)

The required stage position can be found by relating the actual focus $d_{act}$ to the nominal focal depth $d_{nom}$ through:

$$d_{act} = d_{nom}/s = d_{nom} \left(1 + \frac{\langle \phi'_{SA}, D'_{n2} \rangle}{\langle D'_{n2}, D'_{n2} \rangle} \right)$$  \hspace{1cm} (6)

The plot in Fig. 1(d) displays the relationship between $d_{act}$ and $d_{nom}$ as a function of NA. At low NA (in the paraxial regime) the actual focal depth is increased simply by a factor of $n_2/n_1 = 1.45$. At higher numerical apertures (NA $\gtrsim 0.5$), the ratio of $d_{act}$ to $d_{nom}$ starts to increase, reaching $\sim 1.9$ for NA $= 0.95$. This scaling factor is required for accurate 3D fabrication, in order to convert desired structural dimensions $d_{act}$ to the experimental control of the axial separation between specimen and objective lens.

### 2.2. Depth aberration correction range using a SLM

It would be useful to predict the range of depth aberrations that can be successfully corrected using a liquid crystal SLM. Although limited to a $[0, 2\pi]$ rad phase range, large amplitude phase patterns can still be accommodated on SLMs using phase wrapping. The phase wrap transition from $0 \rightarrow 2\pi$ is ideally infinitely sharp but, in real liquid crystal devices there is a finite width $t$ to the phase wrap. Light incident on the area of the SLM occupied by phase wraps does not contribute constructively to the focal formation. Thus, the performance of the SLM starts to diminish as the gradient required in the compensation phase approaches the limit of a $2\pi$ change over the width of the wrap $t$.

From inspection of Fig. 1(c), it is clear that the (dimensionless) maximum gradient $g_{\text{max}}$ in
Fig. 1. (a) Aberration generated during focusing by refraction at an interface. (b) The pupil phase corresponding to the aberration, for a 0.75 NA lens focusing from air ($n_1 = 1$) into fused silica ($n_2 = 1.45$) at $\lambda = 790$ nm to a depth of $d_{\text{nom}} = 100 \, \mu\text{m}$. (c) The phase from (b) with the defocus element removed. (d) A plot showing the ratio of nominal to actual focusing depth as a function of objective NA.

the correction phase occurs at the pupil edge $\rho = 1$:

$$g_{\text{max}} = d_{\text{nom}}' = d_{\text{nom}} \left[ \frac{\text{d}(\phi_{\text{SA}}/d_{\text{nom}})}{\text{d}\rho} \right]_{\rho=1}$$

$$= d_{\text{nom}}' \frac{2\pi \text{NA}^2}{\lambda s} \left( \frac{1}{\sqrt{n_2^2 - \text{NA}^2}} - \frac{s}{\sqrt{n_1^2 - \text{NA}^2}} \right)$$

We set arbitrarily a criterion for the upper bound of aberration compensation that $g_{\text{max}} = \pi/t'$, where $t'$ is the width of a phase wrap normalised to the radius of the effective pupil on the SLM. Using this criterion, in the region of the maximum phase gradient the SLM is expected to modulate the light as desired with approximately 50% of the theoretical maximum efficiency, as phase wraps take up half of the SLM area. If the gradient becomes larger, the efficiency of light modulation at the edge of the pupil will become negligible and effectively reduce the NA of the system. Thus, we can define a maximum depth $d_{\text{max}}$ at which we can perform aberration compensated fabrication using the full NA of the system as:

$$d_{\text{max}} = \frac{\pi}{t' g' s}$$

where we have used Eq. (6) to convert a nominal into an actual focal depth and $g'$, as defined in Eq. (7), is the maximum gradient in the pupil, per unit focussing depth.
The value of $t$ is specific to a particular SLM module. We have previously characterised the SLM for our system (X10468-02, Hamamatsu Photonics), using a technique measuring the first order diffraction efficiency as a function of blazed grating period, to find $t = 1.175$ pixels [25]. Equation (9) depends on the normalised wrap width $t' = t/R$, where $R$ is the physical radius in pixels of the phase pattern on the SLM. This radius is determined by the size of the objective pupil and the magnification between the SLM and objective. However, as a demonstration we take a value of $R = 250$ pixels (the SLM dimensions are $792 \times 600$ pixels, so a phase pattern of diameter 500 pixels fills most of the SLM while allowing some degree of fine adjustment in the alignment). Using this fixed value of $R$, Fig. 2(a) shows the maximum depth $d_{\text{max}}$ as a function of objective lens NA for focusing from air ($n_1 = 1$) into fused silica ($n_2 = 1.45$) at a wavelength of $\lambda = 790$ nm. It is apparent that as the NA increases there is a sharp drop in $d_{\text{max}}$, from the paraxial regime (NA=0.1) where $d_{\text{max}} = 10$ m to $d_{\text{max}} = 120$ $\mu$m at NA=0.95. Figure 2(b) and 2(c) display the associated SLM phase pattern for the 0.95 NA lens, where it can be seen that toward the pupil edge the distance between phase wraps is approximately 2 pixels $\approx 2t$.

3. Experimental system

Figure 3 shows a schematic of the experimental layout. The pulses emitted from the regeneratively amplified titanium sapphire laser (Solstice, Newport/Spectra Physics, 100 fs pulse length, repetition rate 1 kHz, central wavelength 790 nm) were attenuated using a rotatable half-wave plate and a Glan-Laser polariser. The expanded beam was directed onto the reflective phase-only liquid crystal SLM. The SLM and the pupil plane of the objective were imaged onto one another by a 4f system, composed of two achromatic doublet lenses L1 and L2. The focal lengths of L1 and L2 were specified for particular objective lenses to achieve the optimum degree of magnification between the SLM and objective while maintaining a 4f image configuration. Two objective lenses were used in this study: (i) a 0.5 NA 20× Zeiss lens with a pupil diameter of 8.2 mm, a working distance of 1.6 mm and internal correction for focusing through a 170 $\mu$m coverglass. The focal lengths of L1 and L2 were 300 mm and 250 mm respectively, leading to an effective pupil of diameter 490 pixels on the SLM. (ii) a 0.75 NA 80× Olympus
ULWD lens with a working distance of 4.1 mm and no internal correction. To accommodate the smaller pupil of this lens (3.375 mm), L1 and L2 were changed for lenses with focal lengths 400 mm and 150 mm respectively, resulting in a SLM pupil of diameter 450 pixels. The sample used for machining was high grade fused silica (Schott Lithosil Q0) polished on all sides. The sample was mounted on a three axis air-bearing translation stage, (Aerotech ABL10100 (x, y) and ANT95-3-V (z)). An LED illuminated transmission brightfield microscope enabled inspection of the specimen during fabrication.

![Diagram](image)

Fig. 3. The experimental system. All lenses are achromatic doublets. The focal lengths of L1 and L2 are chosen to image the SLM onto the pupil of a particular objective lens with optimum magnification. The phase pattern shown was displayed on the SLM to remove all system induced aberrations.

An initial phase pattern was loaded onto the SLM to remove any system aberrations, including flatness compensation of the SLM itself. This phase pattern was derived following a modal optimisation scheme utilising the focal intensity as feedback [26]. There have been some recent reports that liquid crystal SLMs can lose performance when used to shape high power beams, particularly those with pulse lengths in the nanosecond and picosecond regime. Appropriate schemes have been demonstrated to negate some of these effects, notably by adding additional heat sinking to the SLM module [27]. However, in our system with femtosecond pulses this was not necessary and we saw no change in the SLM performance when irradiated with 0.5 mJ pulses (500 mW), which was the maximum power attainable from our source.

4. Aberration corrected fabrication at NA=0.5

4.1. Single point fabrication

An objective lens with a numerical aperture of 0.5 is routinely used in 3D laser machining, since submicron lateral resolution is achievable combined with working distances of over 1 mm. From inspection of Fig. 2, we expect that the SLM correction of spherical aberration is possible up to depths greater than 1 cm. Indeed, analysis of Eq. (5) predicts that the Strehl ratio [28] remains above 0.8, providing a good indication of near-diffraction limited operation, for focussing over a depth range of 210 µm in fused silica, even without any aberration correction. Since many objectives, including the lens used in this study, are internally corrected for spherical aberration arising from a 170 µm thick coverglass the effective focussing range is up to 380 µm where aberrations have a negligible effect. However, when focussing deeper aberration compensation becomes necessary.

At a depth of 750 µm, the aberration can simply be removed using a phase pattern on the SLM [Fig. 4(a)] as shown by the point fabrication in Fig. 4(b). Each point was fabricated by
five consecutive pulses of energy 0.1 μJ incident in the positive z direction. Five pulses were used, as opposed to one, to create an increased level of uniformity between adjacent fabricated features. The required aberration correction was predicted using the nominal focal depth, which is equivalent to the z stage translation. Feedback aberration correction, using either the energy threshold for fabrication [18, 29] or the intensity of the plasma emission generated in the focal volume [30], was not necessary due to the relatively low sensitivity to the aberration. Without aberration correction [Fig. 4(c)], the pulse energy required for fabrication increases to 0.18 μJ and there are signs of focal elongation. Increasing the pulse energy to 0.3 μJ clearly reveals the focal elongation caused by the aberration: the fabrication stretches over a range of 25 μm along the optic axis. The point at which the material modification is most pronounced is not located in the plane we might expect from Eq. (6), but has shifted approximately 10 μm closer to the surface. This is a direct consequence of the aberrated intensity distribution in the focal region, since the point of maximum intensity is axially shifted from the ‘defocus-free’ plane. The plots contained in the lower part of Figs. 4(b) and 4(c) displaying the expected theoretical intensity distributions with the rms defocus phase removed by Eq. (2) elucidate this point, which is in fact extremely important for accurate 3D fabrication. If the depth induced spherical aberration is not corrected, the actual depth for the peak focal intensity is very hard to predict as the shift is non-linear and discontinuous with respect to focussing depth [31].

At a depth 2.4 mm, corresponding to the full working distance of the lens, the effects of the spherical aberration are very pronounced. Predictive aberration correction using the phase
shown in Fig. 4(d) allowed reliable fabrication of features at the same pulse energy as at shallower depths. The single point fabrication extends over a distance of 4 µm along the optic axis and comprised three voids [Fig. 4(e)]. The presence of multiple voids is due to the multi-pulse nature of the fabrication, where pulses are influenced by the structural modification generated by their predecessors [32, 33]. When appropriate aberration compensation is applied, the train of 5 pulses used for fabrication created either two or three voids closely spaced along the optic axis at all the depths tested. Without any aberration compensation, the pulse energy required for fabrication increased by an order of magnitude and features extended over 100 µm along the optic axis are generated as seen in Fig. 4(f). It is difficult to confirm the driving mechanism behind the axial extent of the features: (i) the spherical aberration arising from refraction at the sample surface is predicted to generate an intensity distribution axially stretched over 100 µm and (ii) the focal distortion dictates that a higher pulse energy is needed for fabrication, raising the peak power in the fused silica above the critical power for self focussing by the Kerr effect [34]. It is likely that the filamentation observed is a combination of these two effects.

4.2. Multi-point fabrication

The analysis of Section 2.2, predicts that aberration compensation is possible to a depth of 1 cm using our experimental system. However, the working distance of the objective limited us to a depth of 2.4 mm, such that the full dynamic range of the SLM could not be fully utilised. Therefore, the remaining flexibility of the SLM could provide additional functionality, such as the generation of multiple foci, while still correcting for the aberration. A hologram was generated using a modified Gerchberg-Saxton algorithm to create a three dimensional face centred cubic lattice of foci around the zero order spot [20]. The intensity of the zero order spot was reduced through destructive interference with an overlaying lattice point. The lattice comprised 196 spots in a $7 \times 7 \times 4$ configuration with a spot separation of 12 µm. The associated phase pattern is shown in Fig. 5(a1).

The multi-foci lattice was initially fabricated at a depth of 0.15 mm, which was essentially aberration free due to the internal coverglass correction of the objective lens. The lattice was accurately fabricated as shown in Fig. 5(b), using ten consecutive pulses of energy 19 µJ. It should be noted that the ratio of this pulse energy to that needed for fabrication from a single focus is 190, where there are 196 spots in the array showing an efficient redistribution of energy by the calculated hologram. At a depth of 2.4 mm, the full working distance of the lens, multi-foci fabrication was achieved with high uniformity and the same pulse energy [Fig. 5(c)] using predictive aberration correction, Fig. 5(a2). Without any aberration correction at 2.4 mm depth, the pulse energy needed to be raised threefold to see clear evidence of fabrication, Fig. 5(d). However, the definition of the lattice is completely lost due to the severe effects of aberrations. The fabrication stretched over 250 µm along the optic axis. Note that although the holograms in Figs. 5(a1) and 5(a2) appear very similar, the small phase change between the two has a marked effect on the fabrication. It can be seen that aberration correction is essential for generating multiple foci holographically in the presence of only moderate aberration. There is sufficient dynamic range from the SLM to both correct the depth dependent aberration and create a large number of foci in a 3D lattice.

5. Aberration corrected fabrication at NA=0.75

In order to demonstrate higher resolution fabrication, we employed a long working distance 0.75 NA objective. Since the axial resolution is proportional to the squared inverse of the NA, an increase in axial resolution by a factor of 2.25 was expected relative to the results of Section 4. However, the analysis of Section 2.2 indicates that there should be an increased sensitivity to the depth-dependent spherical aberration. For this NA, the Strehl ratio drops to 0.8 at a focussing
Fig. 5. (a) Holograms used without (a1) and with (a2) aberration correction. Parallel fabrication with aberration correction at actual depth of 0.15 mm (b) and 2.4 mm (c) in fused silica. Both the structures were fabricated by ten consecutive pulses of energy 19 \( \mu \)J. The focussed laser pulses were incident along the positive \( z \) direction. (d) Parallel fabrication at a depth of 2.4 mm in fused silica without aberration correction, using ten consecutive pulses of energy 57 \( \mu \)J.

depth of just 20 \( \mu \)m in the fused silica. As the objective does not have internal lens correction for spherical aberration, the aberration correction becomes important at all depths.

Single point fabrication is demonstrated in Fig. 6(b) and 6(c) at a depth of 1.1 mm in fused silica. This depth corresponded to the maximum depth \( d_{\text{max}} \) for effective aberration correction predicted by the analysis of Section 2.2. The phase pattern displayed in Fig. 6(a) was used to compensate the aberrations at this depth in a predictive manner. The single point features shown in Fig. 6(b) were generated with this aberration correction, using five consecutive pulses of energy 0.2 \( \mu \)J. The size of the features is \( \sim 1 \mu \)m laterally and \( \sim 3 \mu \)m axially, comparing well to the diffraction limited focus size of this objective. The resolution is comparable to aberration-corrected fabrication at shallower depths, although there is an increase in required pulse energy from 0.05 \( \mu \)J at a depth of 0.1 mm. This is related to the decrease in efficiency of the SLM as the phase pattern becomes more complex, particularly with loss of light at the phase wraps due to the steep phase gradients toward the edge of the pupil. Furthermore, the fabrication could possibly have been improved by employing more accurate feedback based aberration correction [30], since the tolerances to aberration are much tighter at this higher numerical aperture compared to the configuration used in Section 4. However, this was not possible in the current system as the SLM is only able to correct aberrations influencing the fabrication laser beam and not those in the LED illuminated transmission microscope in Fig. 3. A reliable feedback loop
could not be established due to the severe aberrations in this imaging path. When machining at this depth without any aberration correction, Fig. 6(c), the point fabrication required an order of magnitude higher pulse energy and was extremely elongated parallel to the optic axis. The axial elongation was again related to the focal distortion induced by the aberration and possible additional effects from self-focussing.

Fig. 6. (a) Phase pattern used to compensate aberrations focussing to a depth of 1.1 mm in fused silica at NA=0.75 to fabricate the single shot shown in (b) using a pulse energy of 0.2 \( \mu \)J. (c) Single point features fabricated with no aberration compensation, with pulse energies as indicated. (d) Fabrication of continuous features at a depth of 2 mm with (d1 and d2) and without aberration compensation (d3 and d4).

It was still possible to perform controlled fabrication at greater depths than that predicted by the analysis of Section 2.2. Figure 6(d) shows continuous tracks fabricated at a depth of 2 mm in fused silica. At this depth the phase gradient at the edge of the pupil exceeded the capabilities of the SLM. The effect was a reduction in the numerical aperture of the system, an associated reduction in resolution and a higher pulse energy needed for fabrication. The tracks were fabricated by moving the sample at a speed of 25 \( \mu \)m/s with a continuous train of pulses of energy 0.35 \( \mu \)J. The axial extent of the structure shown in Figs. 6(d1) and 6(d2) was approximately 4.5 \( \mu \)m, corresponding to fabrication from an objective lens with an effective NA of \( \approx 0.5 \). If the correction was not applied and pulse energy raised to 1.4 \( \mu \)J the structure shown in Figs. 6(d3) and 6(d4) was generated. There was a high degree of non-uniformity in the structure, with several parts missing. The axial extent of the features increased to 20 \( \mu \)m. Aberration correction was clearly still necessary for precise fabrication at this depth.
Fig. 7. Parallel multi-foci fabrication with a 0.75 NA objective and aberration correction. (a), (b) 196 voxels fabricated simultaneously at a depth of 150 µm. (c), (d) 27 voxels fabricated simultaneously at a depth of 500 µm. The pulses were incident in the z direction.

The larger susceptibility to aberration rendered parallelisation difficult compared to Section 4, since the aberration correction took up a larger proportion of the dynamic range on the SLM. Multi-point lattice structures analogous to those in Section 4, but with the lattice constant reduced to 6 µm, could be fabricated at a depth of 0.15 mm in the fused silica, as can be seen in Figs. 7(a) and 7(b). At depths greater than ~300 µm the spherical aberration induced at the sample interface started to disrupt the formation of the focal array. Even by reducing the number of lattice points to 27 (a 3 x 3 x 3 array) to create a hologram with lower spatial frequency, the multi-foci fabrication only yielded a high degree of uniformity up to depths of ~500 µm, Figs. 7(c) and 7(d). This problem could be possibly resolved by using a dual adaptive element laser fabrication system [29], where an SLM is used for parallelisation while a membrane deformable mirror is used to correct for aberrations.

6. Conclusions

For deep (>1 mm) laser machining in fused silica we have seen aberration correction to be essential, even at relatively low NA. For an objective lens with NA = 0.5, we have shown an SLM to be very effective at maintaining resolution and efficiency over a large depth range. There is sufficient dynamic range that the SLM can additionally provide significant parallelisation (196 separate foci) even at the working distance of the lens (2.4 mm). The single point resolution is maintained at ~1 µm (laterally) x 5 µm (axially) across the full depth range. Without aberration correction, the fabricated features are significantly stretched along the axial direction, in part due to the focal distortion, but also as higher pulse energies are required, thus moving the fabrication into a self-focussing regime. Parallelisation is not possible for depths greater than a few hundred micrometres without aberration correction.

For higher resolution applications an objective with a higher NA is required and the aberration correction becomes even more critical. By applying aberration correction we were able to demonstrate single shot features with a 0.75 NA objective over a depth range of greater than 1 mm in fused silica, maintaining a resolution of ~1 µm x 3 µm. It was still possible to fabricate in a controlled manner using aberration correction beyond this range but, the effective numerical aperture of the system was reduced. In such a case, it would be preferable to use a lower NA objective lens, where the aberrations are not so severe and resolution is maintained throughout the entire axial range of the fabricated structure.

Additionally we have presented a theoretical framework to describe the capabilities and limitations of SLM-based aberration correction, which ties in well with the experimental results. Through prior analysis of the SLM used in the experiment [25], it is possible to predict the range over which diffraction limited focus performance through aberration correction can be expected. This can inform on the appropriate choice of objective lens for a particular application.

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