Focussing over the edge: adaptive subsurface laser fabrication up to the sample face

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Abstract: Direct laser writing is widely used for fabrication of subsurface, three dimensional structures in transparent media. However, the accessible volume is limited by distortion of the focussed beam at the sample edge. We determine the aberrated focal intensity distribution for light focused close to the edge of the substrate. Aberrations are modelled by dividing the pupil into two regions, each corresponding to light passing through the top and side facets. Aberration correction is demonstrated experimentally using a liquid crystal spatial light modulator for femtosecond microfabrication in fused silica. This technique allows controlled sub-surface fabrication right up to the edge of the substrate. This can benefit a wide range of applications using direct laser writing, including the manufacture of waveguides and photonic crystals.

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OCIS codes: (140.3390) Laser materials processing; (090.1000) Aberration compensation; (220.4000) Microstructure fabrication; (130.2755) Glass waveguides; (250.5300) Photonic integrated circuits; (070.6120) Spatial light modulators.

References and links

1. Introduction

Ultrafast laser material processing permits three dimensional fabrication inside transparent substrates. The non-linearity of any absorption coupled with the ultrashort nature of the pulse allows the generation of embedded features confined to the focal volume, without any damage to surrounding regions or the surface [1]. The technique is of increasing interest in the fabrication of a range of devices, such as artificial bandgap materials [2], microfluidic devices [3], metallic nanostructures [4, 5] and photonic waveguide circuits [6, 7].

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, generating a spherical aberration of the focal spot [8]. It has been shown that it is possible to compensate such aberrations and restore diffraction limited performance using adaptive optical elements, both in microscopy [9, 10] and more recently in laser microfabrication [11–13].

There are further unique challenges presented for aberration compensation in laser microfabrication. Taking the example of embedded waveguides in bulk glass, the substrate is often translated perpendicular to the optical axis to create the guiding structure. Near the edge of the substrate, the fabrication efficiency decreases and the effect eventually disappears since a portion of the focused light passes through the side facet of the substrate. The ray trace diagrams in Fig. 1 illustrate the effect for a nominal point of focus moving nearer to the edge of the substrate. Refraction of rays from just a single surface causes focal distortion, but refraction through both the side and top surfaces leads to an additional focal splitting. Thus the quality of fabrication close to the side surface is severely impaired. However, the waveguide needs to be constructed all the way to the side surface in order to achieve efficient coupling of light in and out of the waveguide chip by an external optical fibre. This is currently achieved by mechanically polishing the end faces back to a point where the fabricated waveguide structure is well formed. This step is not only wasteful, but also highly time consuming. Adaptive optical elements have already been implemented into waveguide writing systems to offer a greater degree of flexibility and parallelisation during fabrication [12, 14–17]. Here we further the scope...
Fig. 1. Ray trace diagrams showing the refraction of rays focussed through the top (blue) and side (red) surfaces of a substrate with differing refractive index ($n_2$) to that of the lens immersion medium ($n_1$). The diagrams provide a view of a plane perpendicular to the focal plane and containing the optical axis of the lens. As the lateral distance $g$ between the edge of the substrate and the optic axis decreases, the focal splitting between red and blue rays becomes more severe.

of adaptive optics in ultrafast machining by presenting an optical method of focussing over the edge such that structures can be accurately fabricated right to the edge of a transparent substrate.

2. The aberrated point spread function

Light is considered focussed into a substrate of refractive index (RI) $n_2$ from an immersion medium of RI $n_1$ (Fig. 2). The substrate is bounded by two planes: $T$ (the top surface) with normal parallel to the $z$ axis and $\Sigma$ (the side surface) normal to the $x$ axis. The line of intersection of the two planes (the edge of the substrate) is parallel to the $y$ axis. Illumination is incident along the optic axis $OPF$, which is also parallel to the $z$ axis. $F$ is the geometric, aberration free point of focus within the substrate, while $P$ is the intersection of the optic axis with the top surface $T$. The line $O'QF$ is parallel to the $x$ axis and the point $Q$ designates the intersection of this line with the side surface $\Sigma$. The focussing depth $PF$ is $d$, and the distance from the edge of the substrate $QF$ is $g$.

Light is incident along the optic axis $OPF$. The intersection of the focussing cone with the top surface $T$ is a circular segment bounded by the chord $CC'$, while the intersection with the side surface $\Sigma$ is a hyperbolic segment likewise terminated by the chord $CC'$ (Fig. 2). If the focussing objective lens has a numerical aperture $NA = n_1 \sin \alpha_1$, then the radius of the circular segment on $T$ is given by $R = d \tan \alpha_1$. A general point $A$ within this circular segment on $T$ is described by coordinates $(r_t, \theta_t)$ as shown in Fig. 2. The ray passing through point $A$ makes an angle $\phi$ with respect to the surface normal of $T$, and assuming the objective obeys the sine condition, the following transformation is valid: $\rho = \sin \phi / \sin \alpha_1$. Meanwhile the azimuthal angle must match: $\theta = \theta_t$. Simple geometry gives:

$$\rho = \frac{1}{\sin \alpha_1 \sqrt{1 + \left( \frac{d}{r_t} \right)^2}}$$ (1)

Hence, using the above relationships, it is straightforward to transform the chord $CC'$ described on the surface as: $r_t \cos \theta_t = g$, into the pupil as:

$$\rho = \frac{1}{\sin \alpha_1 \sqrt{1 + \left( \frac{d}{g} \right)^2 \cos^2 \theta}}$$ (2)
Fig. 2. Light is focused to a point F at a depth $d$ beneath the upper surface $T$ of a substrate, and a distance $g$ from the side facet $\Sigma$. The line $CC'$ divides the focusing cone into rays that pass through and are refracted by the top surface $T$ and the side facet $\Sigma$. The line $OPF$ is the optical axis for the focusing lens, while the perpendicular line $O'QF$ represents the optical axis for a virtual pupil, which is used to describe rays passing through the side facet.

providing a boundary within the pupil discriminating between rays passing through either the top or side surface of the substrate. In Fig. 2(a), the rays passing through the top surface $T$ are situated in the shaded part of the pupil inset, while those hitting $\Sigma$ pass through the unshaded area of the pupil.

Having identified whether rays pass through the top or side surface, it is necessary to consider the respective phase aberrations encountered. Such aberrations will arise due to refraction at the substrate surfaces caused by the mismatch in RI between the sample and immersion medium [8]. For rays passing through the top surface, the spherical aberration is the same as for the corresponding ray focussing through an RI mismatch without the edge. The appropriate phase function $\Psi(\rho, \theta)$ which should be applied to the pupil in order to cancel such an aberration is given by [9]:

$$\Psi(\rho, \theta) = \frac{2\pi}{\lambda} d \text{NA} \left( \sqrt{\text{cosec}^2 \alpha_2 - \rho^2} - \sqrt{\text{cosec}^2 \alpha_1 - \rho^2} \right)$$

where $\text{NA} = n_1 \sin \alpha_1 = n_2 \sin \alpha_2$ and $\lambda$ is the wavelength of light in vacuum.

Now it is necessary to consider the aberrations induced by refraction for rays passing through the side facet $\Sigma$. Consider a ray that intercepts $\Sigma$ at point B and makes an angle $\xi$ with the normal to $\Sigma$. The same ray will pass the plane of the top surface $T$ (although not through $T$ itself) at some point A and make angle $\phi$ with the normal to T. It is convenient to introduce a virtual pupil, with optical axis $O'QF$ and a numerical aperture $\text{NA}' = n_1 \sin \alpha_1'$, where the $\alpha_1'$ is the maximum angle (relative to $O'QF$) of any ray that passes through the side face. If rays passing through the surface $\Sigma$ can be considered as originating from the virtual pupil, then the
aberration is equivalent to the form presented in Eq. (3), with the appropriate substitutions:

$$\Psi'(\rho', \theta') = \frac{2\pi}{\lambda} g N A' \left( \sqrt{\csc^2 \alpha'_2 - \rho'^2} - \sqrt{\csc^2 \alpha'_1 - \rho'^2} \right)$$  

(4)

and $NA' = n_1 \sin \alpha'_1 = n_2 \sin \alpha'_2$. In order to determine the appropriate phase required in the real pupil, we must relate $\alpha'_1, \rho', \theta'$ to the variables $\alpha_1, \rho, \theta, g$ and $d$.

Consulting Fig. 2(d), it can be seen that the length $CT$ can be represented as $\sqrt{R^2 - d^2}$, while from Fig. 2(c) $CT$ is also given by $\sqrt{R^2 - g^2}$, such that:

$$R^2 = R^2 - g^2 + d^2$$  

(5)

From above it is known that $R = d \tan \alpha_1$, and similarly $R' = g \tan \alpha'_1$. Inserting these two relations into Eq. (5) allows us to determine the angle $\alpha'_1$ from:

$$g \cos \alpha_1 = d \cos \alpha'_1$$  

(6)

The point B on $\Sigma$ has coordinates $(r_s, \theta_s)$, as indicated by Fig. 2(d). Clearly $\theta_s = \theta'$, while $r_s$ and $\rho'$ are connected by a similar expression to Eq. (1). Noting that $\xi$ and $\phi$ are the angles that a particular ray forms with the $x$ and $z$ axes respectively, we introduce the quantity $\chi$ to represent the angle for the ray with respect to the $y$ axis. A unit vector along $FB$ has a $y$ component $\cos \chi$. Alternatively, by projecting onto the top surface $T$, the $y$ component can also be written as $-\sin \phi \sin \theta$. Thus using direction cosines and remembering that $\theta = \theta_s$, we can write:

$$\cos^2 \phi + \cos^2 \xi + \sin^2 \phi \sin^2 \theta = 1$$  

(7)

Again assuming that the objective obeys the sine rule $\rho = \sin \phi / \sin \alpha_1$, and by analogy in the virtual pupil $\rho' = \sin \xi / \sin \alpha'_1$, Eq. (7) leads to a definition for $\rho'$ as:

$$\rho' = \frac{\sqrt{1 - \rho^2 \sin^2 \theta}}{\sin \alpha'_1}$$  

$$= \frac{\sqrt{1 - \rho^2 \sin^2 \alpha'_1 \cos^2 \theta}}{\sqrt{1 - (g/d)^2 \cos^2 \alpha_1}}$$  

(8)

(9)

Hence the pupil correction phase for aberrations introduced by the refraction of rays at the side facet $\Sigma$, can be ascertained by combining Eq. (4), (6) and (9) to give:

$$\Psi'(\rho, \theta) = \frac{2\pi}{\lambda} g n_1 \left( \sqrt{\left( \frac{n_2}{n_1} + \rho^2 \sin \alpha_1^2 \cos^2 \theta - 1 \right)} - \rho \sin \alpha_1 \cos \theta \right)$$  

(10)

It is interesting to note that Eq. (10) is solely a function of $\rho \cos \theta = x$ and, hence, in this region of the pupil there are only variations in phase along the $x$ axis. As a demonstration, Fig. 3, shows typical pupil phase patterns for a $0.85$ $NA$ objective air lens $(n_1 = 1)$ focussing light of wavelength $\lambda = 790$ nm at a depth of $50$ $\mu$m in a fused silica substrate $(n_2 = 1.45)$, for various distances from the edge (values of $g$). Equation (2) gives the boundary $CC'$ in the pupil, while Eq. (3) and (10) give the respective corrective phase distributions for the two pupil regions. There is necessarily a discontinuity in the pupil phase along the chord $CC'$ when separating the pupil into rays passing through $T$ and $\Sigma$. However, this can be easily accommodated by a liquid crystal phase-only spatial light modulator (SLM), which operates in the range $[0, 2\pi]$ radians.

It should be noted that when adaptively correcting spherical aberration, either in microscopy
or microfabrication, it is common to remove the defocus element of Eq. (3) to reduce the amplitude of the correction phase [18]. In doing so, the focal distortion due to the RI mismatch is corrected, but the focal depth is not restored to the geometric focus. However, in the present situation, it is important to retain the full form of Eq. (3), such that rays intercepting \( T \) and \( \Sigma \) overlap at the geometric focus.

### 3. Experimental layout

Figure 4 shows a schematic of the experimental layout. The pulses emitted from the regeneratively amplified titanium sapphire laser (Solstice, Newport/Spectra Physics, pulse length 150 fs, 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 a reflective liquid crystal phase-only SLM (X10468-02, Hamamatsu Photonics). The SLM and the pupil plane of the objective were imaged onto one another by a 4\( f \) system, composed of two achromatic doublet lenses. A 500 \( \mu \)m diameter pinhole on an adjustable mount was inserted into the Fourier plane of the SLM and initially positioned to transmit all light incident on the SLM. The beam fully illuminated the back aperture of a Leitz NPl 50\( \times \) objective with a 0.85 numerical aperture. The substrate 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 illuminated the specimen during fabrication.

The samples employed were high purity fused silica (Schott Lithosil Q0) with both the top and side facets polished to an optical quality. Initially, the SLM was set to display a corrective phase pattern that eliminated any system induced aberration, such that the there was a flat phase distribution in the pupil of the objective lens. The focal splitting (as per Fig. 1) caused by the edge aberration is easily observed when focussing near the edge of the sample. The image in Fig. 4(b) shows a row of four voids, each fabricated by a single laser pulse at a nominal focal depth \( d_{\text{nom}} \) of 50 \( \mu \)m and 5 \( \mu \)m from the side facet. The pulses were incident along the negative \( z \) direction. There is clear void fabrication at depths \( Z_1 \) and \( Z_2 \) either side of \( d_{\text{nom}} \) due to the focal splitting discussed above, whereby rays passing through the side facet focus to a different point to those refracted at the top facet. Figures 4(c) and 4(d) are images showing the fabricated voids in the perpendicular plane, focused at depths \( Z_1 \) and \( Z_2 \) respectively. Figure 4(d) clearly demonstrates the spread of fabrication further into the sample away from the optic axis due to the refraction of rays through the side facet. Overall, there is a good correspondence between the observed fabrication and the ray tracing shown in Fig. 1.
Fig. 4. (a) Experimental schematic for microfabrication demonstrations. Lens focal lengths are in mm. (b), (c) and (d): Images of focal splitting in void fabrication of fused silica after exposure to a single pulse at a nominal depth of 50 μm and 5 μm from the substrate edge. The optical axis is the z direction. (c) and (d) are cross-sectional images focused at planes Z_1 and Z_2 respectively.

4. Plasma emission measurements and void fabrication

We implemented an adaptive aberration correction procedure to compensate the detrimental focal splitting effect. For this purpose, we employed a feedback metric that was related to the nature of the light distribution at the focus. When an ultrafast laser is focused into a transparent material, a plasma is generated within the focal volume. The plasma is generated by multiphoton absorption and avalanche effects and does not necessarily indicate the destruction of the surrounding material matrix. Under strong focusing conditions, the plasma emission is mostly isotropic and unpolarized [19]. Previously it has been shown that the plasma emission intensity is an appropriate feedback metric for performing aberration correction using adaptive optical elements during fabrication [20]. The plasma emission intensity is greatest when any aberrations are minimised; this corresponds to the generation of the smallest fabricated features for a given input pulse energy.

Here we employed measurements of the focal plasma emission intensity to modify the phase pattern displayed on the SLM and minimise aberrations generated when focusing near the edge of the sample. With a flat phase pattern assigned to the SLM, the top surface was located by noting the z position of the specimen which had the lowest threshold pulse energy for surface fabrication. The sample was then translated to a nominal depth d_{nom} and distance from the edge facet g_{nom}. Using the values of g_{nom} and d_{nom} as a starting point, various phase patterns were applied to the SLM and the sample was irradiated with a continuous train of pulses with energy below that required for void formation. To measure the plasma emission intensity, the LED illumination (Fig. 4) was switched off and the focal volume was imaged onto the CCD. A typical image is shown in the inset of Fig. 5(b).

Figure 5 shows measurements of the plasma emission intensity at a nominal focal depth of d_{nom} = 50 μm and distances from the substrate edge g_{nom} = 5, 10 and 15 μm. The sample was kept stationary and the SLM phase pattern was altered while monitoring the plasma intensity. In Fig. 5(a) the edge correction was varied while the depth correction remained constant. Note this corresponds to changing the value of g in Eq. (2) and (10), which alters both the position.
Fig. 5. Measurements of the net intensity of plasma emission from the focal volume when focussing at a nominal depth $d_{\text{nom}} = 50 \, \mu\text{m}$ in fused silica, at nominal distances of $g_{\text{nom}} = 5 \, \mu\text{m}$, $10 \, \mu\text{m}$ and $15 \, \mu\text{m}$ from the edge of the substrate. In (a) the phase pattern in region A of the SLM is altered by varying $g$ in Eq. (10), while in (b) the phase distribution in region B is modified by varying $d$ in Eq. (3). The boundary $CC'$ separating region A and B varies according to Eq. (2) in both plots. A background phase is added to the calculated phase distributions, which takes into account any system aberrations including the initial flatness correction for the SLM. The inset shows a typical CCD image of the plasma emission. The weak signal on the left is a ghost image formed by light reflecting off the internal side surface of the silica block.

of the chord $CC'$ and the form of the phase modulation in region A of the SLM (as denoted in the inset of Fig. 5). The form of the phase pattern in region B of the SLM depends solely on $d$, which remained constant as $d_{\text{nom}}$. Six sets of measurements were taken at different points along the substrate edge by both increasing and decreasing applied values of $g$ either side of $g_{\text{nom}}$.

Figure 5(a), shows a sharp peak in the plasma emission intensity, for values of $g$ close to $g_{\text{nom}}$. This point corresponds to rays passing through both the top surface and side facet focussing to a common point, and hence generating the maximum plasma at the focus. This should also lead to fabrication of the tightest features at the lowest pulse energies. High repeatability in the peak position and relatively low error across the measurements sets ($\sim 2\%$) indicate the reliability of the technique.

Decreasing $g$ from the optimum value, it is obvious that the plasma emission should decrease, because the change in the position of the chord $CC'$ renders a greater portion of the pupil subject to the correction function described by Eq. (10). Thus, rays actually passing through the top surface of the substrate are corrected as though they were passing through the side surface. This will lead to a decrease in focal intensity. However, increasing $g$ from the optimum value should have no effect on rays passing through the top surface. Hence, the sharp drop in plasma...
intensity for \( g > g_{\text{nom}} \) demonstrates that Eq. (10) is appropriate for the phase correction of rays passing through the side surface and removes any focal splitting.

In Fig. 5(b), the plasma emission intensity is monitored as a function of differing depth corrections with the sample stationary at a nominal depth of 50 \( \mu \text{m} \) and 10 \( \mu \text{m} \) from the side surface. This corresponds to changing the value of \( d \) in Eq. (2) and (10), again altering the position of the chord \( CC' \), but now also modifying the form of the phase modulation in region B of the SLM. The measurements were made in a similar manner to those presented in Fig. 5(a), only by altering \( d \) and keeping \( g \) fixed at \( g_{\text{nom}} \). There is again a peak in the plasma emission intensity as the value of \( d \) varied through \( d_{\text{nom}} \). The peak is not as sharp as that found when varying \( g \), possibly related to the natural focal elongation along the axial direction. However, this still demonstrates the necessity to have the correct values of both \( d \) and \( g \) in order to provide appropriate aberration correction, relating to maximum overlap of rays in the focal volume.

![Fig. 6. Differential interference contrast (DIC) images showing voids fabricated at a depth of 50 \( \mu \text{m} \) in fused silica, 10 \( \mu \text{m} \) from the edge of the substrate. The optical axis was along the \( z \) direction and the voids were fabricated by a burst of 100 pulses from the laser.](image)

While the plasma emission measurements exhibit the success of the edge correction technique, a more tangible demonstration can be found by observing results of the improvement in fabrication. Figure 6 shows images of voids fabricated at a depth of 50 \( \mu \text{m} \) in fused silica at a distance of 10 \( \mu \text{m} \) from the edge of the substrate. Sets of 3 voids, separated laterally by 5 \( \mu \text{m} \) were generated by a burst of 100 pulses with energies of 90, 110 and 130 nJ as indicated in Fig. 6. Voids were generated firstly with aberration correction for rays passing through both the top and side surfaces (“Edge corrected”), and subsequently with aberration correction purely for the RI mismatch at the top surface neglecting the edge of the substrate (“No edge correction”). In the \( x-y \) plane (with the optic axis along \( z \)) the void fabrication seems stronger for a given power with the edge correction applied. By viewing in the \( x-z \) plane, Fig. 6, it is clear that when the edge correction is applied, there is greater axial confinement in the void features. The lateral and axial dimensions of the ‘edge-corrected’ voids are \( \lesssim 1 \mu \text{m} \) and \( \sim 1.8 \mu \text{m} \) respectively, coinciding well with the expected dimensions considering the numerical aperture of the objective. Thus, we can see that the edge correction method minimizes the aberration to a level
which is useful for fabrication. With no edge correction applied, there is axial elongation of the fabricated features and evidence of focal splitting due to rays passing through the side facet of the substrate.

5. Fabrication of tracks with power variation

One of the main areas of application for this technique promises to be the means for generating high quality direct laser written waveguides right up to the edge of a substrate, eliminating the time-consuming requirement of cutting and polishing the end surfaces. To investigate this possibility, we wrote tracks up to the edge of the fused silica sample used in the previous section for void formation. The translation speed was 0.5 $\mu$m/s perpendicular to the edge at a depth of 50 $\mu$m. Feedback from the translation stages was used to automatically update the amount of edge correction applied to phase patterns displayed on the SLM. The emission from the laser was a continuous pulse train (repetition rate 1 kHz) and the power was kept constant. The results are shown in Fig. 7(a). The SLM phase pattern was kept constant during fabrication of track (i), but track (ii) was written with automatically updated edge correction. It can be seen that the edge correction has a beneficial effect in maintaining fabrication up to the side surface for (ii) in contrast to track (i). However, it is clear that the degree of fabrication is still reduced as the focus nears the side surface. Such an effect is indeed to be expected since reflection of incident light from the side facet will be stronger than that from the top surface as the rays are incident at greater angles to the surface normal. Henceforth, to fabricate a spatially invariant structure some variation in the writing power is also required.

![Fig. 7. DIC images showing tracks fabricated at a depth of 50 $\mu$m in fused silica, by translating the sample at a speed of 0.5 $\mu$m/s in the positive x direction. The tracks in image (a) were written at a constant power without (i) and with (ii) correction of the edge aberration. The tracks in images (b) and (c) were written adapting the SLM to modify the laser power incident on the objective lens, and in image (b) the SLM additionally provided correction of the edge aberration. The optical axis was along the z direction. Also shown are the instantaneous phase patterns displayed on the SLM at the points indicated.](image)

The laser power is generally controlled in the current experimental layout using a combination of a half-wave plate and polariser immediately following the laser output. However, for the purposes of automation it is more convenient to attenuate the writing beam using the SLM, since this is continually updating to provide the optimum edge correction. Therefore a blazed grating was overlayed onto the SLM phase pattern directing the proportion of light needed for fabrication into the first diffraction order. The zero order was blocked by adjusting the pin-hole position in the Fourier plane of the SLM (see Fig. 4). The intensity in the first diffracted order $I_1$, and hence the fabrication beam, was maximum for a modulation depth ($\phi_o$) of the
blazed grating equal to \(2\pi\) radians, and subsequent variation in \(\phi_o\) enabled adjustment of the power passing into the focus. The experimental dependence of \(I_1\) on \(\phi_o\) was found to show good correspondence to the theoretical prediction \(I_1 \propto \text{sinc}^2(1 - \phi_o/2\pi)\) [21]. The blazed grating employed had a period of 0.6 mm (30 pixels), with an associated diffraction efficiency of 91\% when \(\phi_o = 2\pi\). The grating was orthogonal to the tilt introduced due to the edge correction described by Eq. (10), causing the fabrication focus to be laterally shifted parallel to the substrate edge.

The phase patterns displayed in Fig. 7(b) and 7(c) demonstrate how the blazed grating may be used in conjunction with the above analysis, to correct for the induced aberration and vary the incident power. Note that when a corrective phase pattern is added to a blazed grating with modulation depth \(\phi_o = 2\pi\) (as near the substrate edge in Fig. 7(b) and 7(c)), the resulting phase pattern displayed on the SLM after implementing the modulo \(2\pi\) operation appears identical except for a uniform tilt across the pupil. This is expected since the light is efficiently directed into the first diffracted order. Away from the substrate edge in Fig. 7(b) and 7(c), where the blazed modulation depth is \(\phi_o < 2\pi\), the resultant phase pattern displayed on the SLM is easily recognisable as a grating and causes the light to be split into multiple orders, of which only the first is used for fabrication while all other light is blocked in the Fourier plane of the SLM.

The required power variation was firstly ascertained by monitoring the plasma emission intensity as a function of distance from the edge of the substrate. The blazed grating modulation depth was then adjusted to maintain a constant plasma emission intensity at all points. This was done both when the SLM phase pattern was updated to give edge correction and for a static phase pattern on the SLM providing only depth correction. The tracks written using the SLM to provide edge correction and power variation (Fig. 7(b)) create uniform features right up to the edge of the substrate. This was not possible without the edge correction routine, as seen in Fig. 7(c), as there is evidence of focal splitting near the substrate edge.

6. Summary and discussion

We have calculated the aberrations introduced when light is focused into a transparent medium close to the edge of the substrate. A ray tracing approach predicted that the refraction of rays by the top and side facets of the sample creates two separate aberrated foci. This phenomenon was confirmed by fabrication of voids in fused silica using ultrafast laser illumination. We determined the appropriate phase distribution in the pupil of the objective that could correct for the aberration, involving a phase discontinuity mapping the boundary of the substrate to the pupil. Such phase distributions can be readily implemented using a liquid crystal phase-only SLM. We demonstrated the effective correction of such edge aberrations in an ultrafast laser fabrication system close to the edge of a fused silica block through plasma emission measurements, void formation and tracing continuous tracks to the edge of the substrate. Due to the focal splitting, it is impossible to overcome the aberration by increasing the power of the fabrication beam, since this generates additional unwanted features.

It should be noted that whilst the analysis presented here is based around aberrations of monochromatic light at the centre wavelength, the practical results show that the correction was effective for the finite bandwidth of the fs-pulsed laser. As the system described here only corrects phase aberrations modulo \(2\pi\) radians, we have not taken into account temporal effects of the pulse. However, if short pulsed lasers are employed, as in this article or for applications such as non-linear microscopy, there are some additional constraints that must be considered. It is clear that the rays passing through the top facet of the sample have to pass through a greater expanse of material than those incident on the side facet and, hence, are delayed in reaching the focus. This effectively limits the depth range over which the pulses from the two sets of rays will overlap temporally (\(d < \sim 50\ \mu\text{m}\) in this present study), dependent on the refractive index.
of the substrate and the pulse duration. Nevertheless, at greater depths the phase correction employed here is still relevant. While the pulse might be temporally split, all components are focussed to the same point in the substrate and hence will only fabricate at that point even if the incident power were increased. This temporal splitting will not occur at all for continuous wave lasers or, in most practical situations, lasers with pulse lengths of a picosecond or longer.

Acknowledgments

This research was supported by funding from the Engineering and Physical Sciences Research Council, UK (grant numbers EP/H049037/1 and EP/E055818/1).