# Shaping ultrafast laser inscribed optical waveguides using a deformable mirror

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**Abstract:** We use a two-dimensional deformable mirror to shape the spatial profile of an ultrafast laser beam that is then used to inscribe structures in a soda-lime silica glass slide. By doing so we demonstrate that it is possible to control the asymmetry of the cross section of ultrafast laser inscribed optical waveguides via the curvature of the deformable mirror. When tested using 1.55 µm light, the optimum waveguide exhibited coupling losses of ≈ 0.2 dB/facet to Corning SMF-28 single mode fiber and propagation losses of ≈ 1.5 dB.cm$^{-1}$. This technique promises the possibility of combining rapid processing speeds with the ability to vary the waveguide cross section along its length.



**OCIS codes:** (130.3120) Integrated optics devices; (140.3390) Laser materials processing.

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## 1. Introduction

In 1996, Davis et al demonstrated that optical waveguides could be inscribed in glass using ultrafast laser pulses [1]. The ultrafast laser waveguide inscription field is now relatively mature, but much remains to be learned about how the inscription can be controlled. When inscribing waveguides the distribution of the photo-induced refractive index change is a key parameter, as this determines the properties of the transverse modes guided by the waveguide. Various waveguide shaping techniques (slit-beam shaping [2], astigmatic focusing [3], multiscan technique [4]) have been demonstrated. Although impressive results have been achieved using these techniques, each exhibits significant limitations. More specifically, the slit-beam shaping and astigmatic focusing techniques that rely on beam shaping to control the waveguide cross section are inflexible and result in waveguides with cross sections that change if the waveguide performs a bend. The multiscan technique on the other hand provides almost complete flexibility in defining the waveguide cross section along its length, but is slow due to the requirement for multiple passes. Here we demonstrate that the waveguide cross section can be controlled by shaping the laser beam profile using a two-dimensional deformable mirror. In comparison to all previous shaping techniques, this technique may offer the unique possibility of combining rapid processing and flexible control of the waveguide shape regardless of translation direction.

## 2. Waveguide inscription regimes and writing geometries

When an ultrafast pulse of sub-bandgap radiation is focused inside a dielectric material that is normally transparent to the laser wavelength, optical energy can be deposited in the material at the focus through a combination of nonlinear multi-photon absorption, tunneling ionization and avalanche ionization [5]. The deposited energy can induce highly localized structural changes in the material which can manifest themselves in a variety of ways, one example of which may be a refractive index change. This refractive index change can then be used to inscribe optical waveguides by translating the material through the focus [1].

The exact form of the refractive index change is dependent on the sample composition itself and eight fabrication parameters known so far (*pulse energy, scan speed, wavelength, focusing geometry, repetition rate, pulse duration, polarization and translation direction*) [6, 7], and many materials exhibit either a negative- or birefringent refractive index change after irradiation. If we assume however that the repetition rate of the laser is low enough to ignore heat accumulation effects [8], and that the material exhibits a non-birefringent increase in refractive index after irradiation, the distribution of the refractive index change is related to the distribution of the free electron plasma induced by the pulse. This in turn is related to the distribution of the electric field (E-field) in and around the focus [3]. For the rest of the paper we will consider only this fabrication regime and will refer to it as the low-repetition rate regime (LRR-regime).

Waveguides can also be inscribed using two primary writing geometries [3]. In the first, the longitudinal writing (LW) geometry, the sample is translated primarily along the direction of propagation of the laser beam. In the second, the transverse writing (TW) geometry, the sample is translated in the plane perpendicular to the direction of propagation of the laser beam. Although waveguides that are inscribed using the LW-geometry and a focused circular Gaussian beam exhibit inherently symmetric cross sections due to the rotational symmetry of the laser beam, the LW-geometry suffers from a number of practical drawbacks. Firstly, as the waveguide is inscribed, the degree of spherical aberration imparted on the laser beam by the sample varies, changing the properties of inscribed waveguide along its length. Secondly, the

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maximum waveguide length is limited by the working distance of the lens. For these reasons, the TW-geometry has attracted significantly more attention. When inscribing waveguides in the LRR-regime using a TW-geometry and a focused circular Gaussian beam, the dimensions of the inscribed waveguide are directly related to the confocal parameter and beam waist of the focus [3]. Waveguides fabricated in the LRR-regime using the TW-geometry therefore suffer from a high degree of asymmetry unless corrective steps are taken. Waveguide asymmetry may result in asymmetric transverse mode distributions and waveguide birefringence. This in turn can induce high coupling losses and polarization dependent losses. Consequently it is important to minimize the waveguide asymmetry for many applications. The rest of this paper deals with shaping waveguides inscribed in the LRR-regime using a TW-geometry.

## 3. Shaping ultrafast laser inscribed waveguides

A number of techniques have been developed to control the cross section of waveguides inscribed in the LRR-regime using a TW-geometry. These techniques either rely on beam shaping to control the E-field distribution in and around the focus [2, 3], or on scanning the sample through the focus multiple times to construct the desired cross section, the so-called multiscan technique [4]. The beam shaping techniques have the advantage that since any individual pulse modifies the entire waveguide cross section, structures such as Bragg–waveguides, that combine Bragg-gratings with an optical waveguide, can be readily inscribed by modulating the laser power during the inscription [9, 10]. Beam shaping techniques also exhibit a number of disadvantages however. Firstly, the waveguide shape is set by the optics and cannot be readily altered along its length. Secondly, beam shaping techniques rely on decoupling the beam waists in the axis parallel and perpendicular to the waveguide axis, and as a consequence the waveguide shape changes if the waveguide performs a bend [11]. In contrast to the beam shaping techniques, the multiscan technique enables almost complete freedom in defining the waveguide cross section along its length, but has the disadvantage that it is slower and it would be difficult to inscribe Bragg-waveguides, as this would require the spatial phase of the modulation for each scan to precisely match. Clearly, a beam shaping technique that could provide the benefits of beam shaping while giving the flexibility of the multiscan technique would be of great practical interest.

## 4. Waveguide shaping using a deformable mirror

One of the most intuitive beam shaping techniques is the “slit beam shaping” technique, first demonstrated by Cheng et al [12] and then applied to waveguide inscription by Ams et al [2]. In this technique, a slit is placed in front of the microscope objective used to focus the laser beam inside the substrate. The slit is orientated parallel to the sample translation direction and its purpose is to reduce the numerical aperture of the focused beam in the axis perpendicular to the waveguide axis, increasing the laser spot size in this axis and widening the width of the modified region. Using a two-dimensional deformable mirror it is possible to replicate the slit beam shaping technique by focusing the beam in only one axis to produce a line focus in front of the microscope objective. In contrast to the slit beam shaping technique, the two-dimensional deformable mirror offers the possibility of varying the width and orientation of the line focus during the inscription.

#98157 - $15.00 USD Received 1 Jul 2008; revised 29 Jul 2008; accepted 4 Aug 2008; published 7 Aug 2008

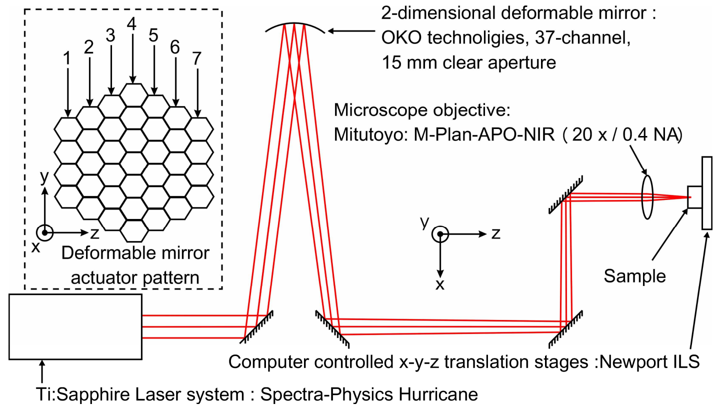


Fig. 1. Diagram of the experimental configuration used to inscribe waveguides. The inset shows the deformable mirror actuator pattern. Each column of actuators is labeled 1 to 7.

Figure 1 is a diagram of the experimental configuration used during the investigation. The inscription laser was a regeneratively amplified Ti:sapphire laser emitting ≈ 130 fs (FWHM) pulses of 800 nm radiation at a repetition rate of 5 kHz. The collimated laser beam was first projected onto a two-dimensional deformable mirror (OKO technologies, 37 channel, 15 mm clear aperture) and then into a microscope objective (Mitutoyo M-PLAN-APO-NIR (20×, 0.4 NA)) placed just over 2.0 m away from the deformable mirror. When the deformable mirror was set to flat, the intensity profile of the collimated laser beam was slightly irregular but could be approximated by a two-dimensional Gaussian. Using the knife edge technique, the $1/e^2$ diameters of the beam were measured to be ≈ 5.0 and ≈ 7.2 mm in the x- and y-axis respectively. The collimated laser beam therefore only partially filled the 1.0 cm clear aperture of the microscope objective, resulting in effective focusing numerical apertures of ≈ 0.2 and 0.3 in the x- and y-axis respectively. The distance from the deformable mirror to the microscope objective was chosen as a consequence of initial studies that indicated that the minimum focal length of the deformable mirror was ≈ 1.5 m. The purpose of the microscope objective was to focus the laser beam inside a soda-lime silica glass slide (Menzel-Gläser Extra-white Electroverre-Glass) whose chemical composition was 72.2 % $SiO_2$, 14.3 % $Na_2O$, 6.4 % CaO, 4.3 % MgO , 1.2 % $Al_2O_3$, 1.2 % $K_2O$, 0.3 % $SO_3$, 0.03 % $Fe_2O_3$ [13]. This substrate material has been used by us in previous work [14], where the slit-beam shaping technique was used to control the cross section of the inscribed waveguides. Since beam shaping was shown to be a suitable technique for this material, it is reasonable to expect that the results of this paper will be transferable to other materials such as phosphate glass [2, 3] and fused silica [11] where beam shaping has been used successfully in the past. Structures were inscribed ≈ 300 μm below the substrate surface using a TW-geometry. For the purposes of this paper we will define the sample translation direction as the y-axis, the laser beam propagation direction directly before the microscope objective as the z-axis and the axis orthogonal to both the z- and y-axis as the x-axis. For all experiments, the laser beam was linearly polarized along the x-axis.

Prior to using the deformable mirror to shape the beam, a preliminary study was conducted to ascertain what slit width would be required to inscribe structures with a symmetric cross section. It was found that structures with a close to symmetric cross section could be inscribed when the collimated laser beam was passed through a 500 μm wide slit oriented along the y-axis, and placed 9.0 cm in front of the microscope objective. For this preliminary study the sample was translated at a velocity of 1.0 $mm.s^{-1}$ and pulse energies ranging from ≈ 2.0 μJ to 8.0 μJ were investigated. The asymmetry of the modified region was found to be insensitive to pulse energy over the range investigated, although it did increase in size as the pulse energy was increased. In an attempt to replicate the effect of the slit using only the deformable mirror

#98157 - $15.00 USD Received 1 Jul 2008; revised 29 Jul 2008; accepted 4 Aug 2008; published 7 Aug 2008

to shape the beam, the laser was focused through the slit, in only the x-axis, by adjusting the voltages applied to each column of mirror actuators, as shown in the inset of Fig. 1. The mirror used in this study was of the "free-standing membrane" type where a very thin reflective membrane is suspended over an array of electrode actuators. Any applied voltage potential between the membrane and the actuators deforms the mirror by pulling the mirror towards the actuator. Through carefully optimizing the deformable mirror actuator voltages in an iterative manner, the transmission through the slit was increased by a factor of 4 to 34 %. The actuator voltage pattern that achieved this transmission will be referred to as mirror setting "A"

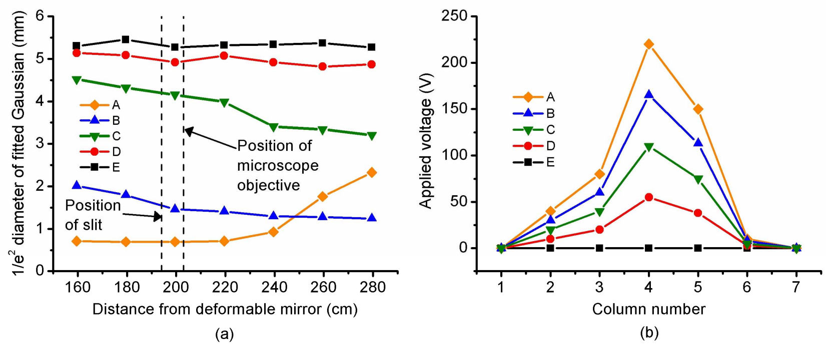


Fig. 2. (a). $1/e^2$ diameter of the Gaussian fitted to the x-axis intensity profile of the laser beam as a function of distance away from the deformable mirror for 5 different mirror settings. (b) Deformable mirror actuator voltage patterns used during the investigation.

The focusing characteristics of the deformable mirror were investigated by projecting the laser onto a charged-coupled device (CCD) camera whose position could be varied in the vicinity of the slit. The diameter of the laser beam at each location was characterized by fitting a one dimensional Gaussian function to the x-axis intensity distribution of the laser beam sampled at approximately the middle of its y-axis distribution. Figure 2(a) plots the $1/e^2$ diameter of the fitted Gaussian as a function of distance from the deformable mirror for the five mirror settings shown in Fig. 2(b). Mirror settings "B", "C", "D" and "E" were created by scaling the "A" mirror setting voltages by factors of 0.75, 0.5, 0.25 and 0 respectively. As the voltage applied to the mirror is increased, the mirror curvature increases, moving the focus towards the position of the slit. Figure 2(a) confirms that mirror setting "A" creates a focus at the position of the slit. After the deformable mirror focusing had been characterized, the slit was removed and structures were inscribed using the five different mirror settings, a sample translation velocity of 500 $\mu m.s^{-1}$ and pulse energies (as measured before the microscope objective) of 1.0 to 5.0 µJ in steps of 1.0 µJ. After inscription, the waveguide facets were polished. The final waveguide length was 25.0 mm.

## 5. Results and discussion

The morphology of the inscribed structures was inspected using an optical microscope. Figure 3(a) shows transmission mode optical micrographs of the cross sections of the structures inscribed using 5.0 µJ pulses. Each image was obtained by imaging slightly under the facet surface, firstly because the images of the cross sections became significantly more pronounced by doing so and secondly because the facets consistently cracked after polishing, presumably due to stress relief at the surface. We suggest that a more pronounced image is obtained by imaging slightly under the exposed end facet for two reasons. The first reason is that by imaging under the facet, the structure then extends through the full depth-of-field (DOF) of the image. This produces a more pronounced image of the structure than imaging directly on the exposed facet which only partially fills the DOF with the structure. The second reason is that imaging below the facet reduces the effect of facet imperfections (such as cracking) on the image contrast and clarity. Figure 3(b) shows CCD images of the inscription

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laser beam directly before entering the microscope objective for each of the five mirror settings. As shown in Fig. 3, the width of the modified region along the x-axis increases as the mirror curvature increases, a trend that we directly attribute to the reduction in the effective numerical aperture in the x-axis as the deformable mirror voltages are increased. As shown in Fig. 3(a) the morphology of the structures inscribed using deformable mirror settings “A” and “B” does not vary smoothly across the cross section of the modified region but instead exhibits significant structure within. This may be related to the fringes clearly visible on the laser beam profile for mirror setting “A” shown in Figs. 3(b)-3(i), and only just visible on the laser beam profile for mirror setting “B” shown in Figs. 3(b)-3(ii). Further investigation is necessary to determine the origin of these fringes, but they are almost certainly the result of aberrations in the focusing by the deformable mirror.

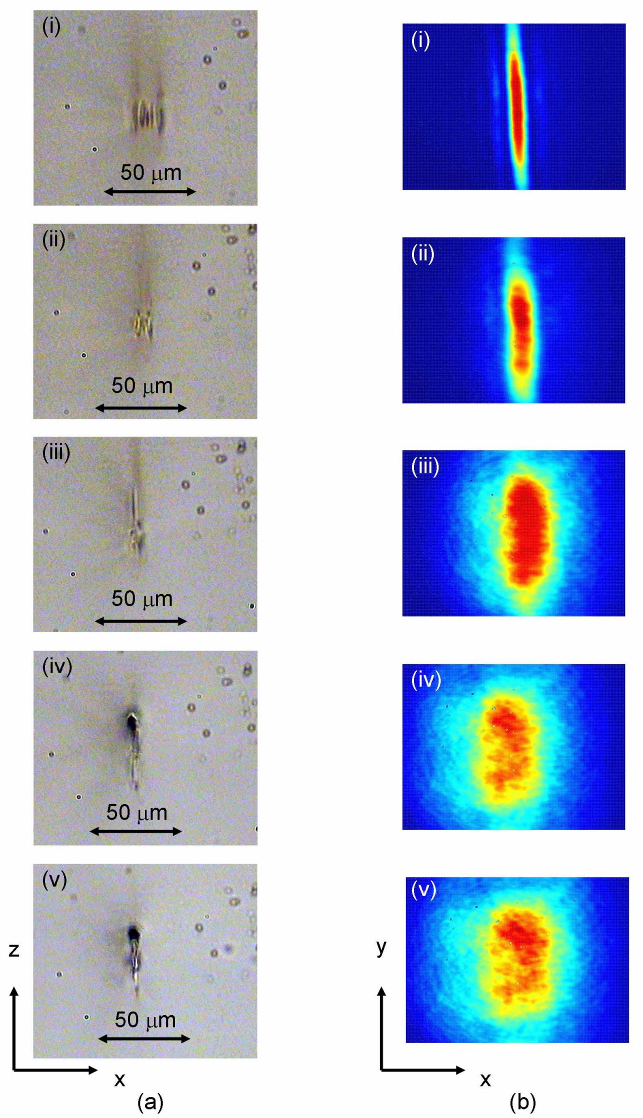


Fig. 3. (a). Transmission mode optical micrographs of the cross sections of the features inscribed using 5.0 μJ pulses and deformable mirror settings (i) “A”, (ii) ”B”, (iii) “C”, (iv) ”D” and (v) “E”. The contrast of the micrographs has been adjusted to make them clearer. (b) CCD camera images of the laser beam directly before the microscope objective for deformable mirror actuator settings (i) “A”, (ii) “B”, (iii) “C”, (iv) ”D” and (v) “E”.

#98157 - $15.00 USD Received 1 Jul 2008; revised 29 Jul 2008; accepted 4 Aug 2008; published 7 Aug 2008

The guiding properties of the inscribed structures were investigated qualitatively by imaging one end of the structure onto an IR-Vidicon camera while coupling 1.55 μm light into the structure at the opposite end. Guiding was observed only for structures fabricated using mirror settings “A”, “B” and “C”. From this simple observation we conclude that the x-axis size of the structures inscribed using deformable mirror settings “D” and “E” was too small, and the refractive index contrast of the structures was too low, for guiding at 1.55 μm. It is clear therefore that beam shaping was necessary to widen the structure enough to support the mode.

The guiding properties of the waveguides were investigated in a quantitative manner by measuring the insertion loss (IL) of each waveguide at 1.55 μm. This was done by breaking a Corning SMF-28 fiber patchcord in two and butt coupling the cleaved fibers to either end of the waveguide using index matching gel. The IL was defined as the difference in signal power measured when the fibers were coupled to the waveguide and when the patchcord was unbroken. All waveguides fabricated using the “C” deformable mirror setting were found to exhibit high polarization-dependent losses (PDLs) and high insertion losses (> 8.0 dB), most probably due to a combination of a highly asymmetric core shape and optical damage. No guiding was observed for the structure inscribed using 1.0 μJ pulses and mirror setting “A”, and only a loosely confined mode was observed for the waveguide inscribed using 1.0 μJ pulses and mirror setting “B”. All structures inscribed using pulses energies of 2.0 μJ and greater, and mirror settings “A” and “B”, supported a well confined single mode and exhibited PDLs of 0.3 dB or less. Waveguides inscribed using both mirror settings “A” and “B” exhibited a general decrease in insertion loss as the pulse energy was increased. Examination of the guided modes indicated that increasing the fabrication pulse energy increased the effective refractive index contrast of the inscribed waveguide. This improved the fiber-waveguide mode overlap resulting in reduced fiber-waveguide coupling losses and lower ILs. Waveguides inscribed using mirror setting “B” exhibited consistently lower IL’s than those inscribed using mirror setting “A” and the same pulse energy. We observed that the transverse modes supported by waveguides inscribed using mirror setting “A” were larger and less matched to the fiber mode than comparative structures inscribed using mirror setting “B”. This resulted in higher fiber-waveguide coupling losses and higher ILs for waveguides inscribed using mirror setting “A”. Table 1 summarizes the characterization results for each waveguide fabricated using mirror settings “A” and “B” that exhibited the lowest insertion loss. As shown in Table 1, the overall “optimum" waveguide was fabricated using mirror setting “B” and 5.0 μJ pulses. All coupling losses and propagation losses listed in Table 1 were evaluated using the multimode fiber technique described in [15].

Table 1. Characterization results for each waveguide fabricated using mirror settings “A” and “B” that exhibited the lowest insertion loss.

| Mirror setting | Pulse energy (μJ) | Insertion loss (dB) | Polarization dependent loss (dB) | Coupling loss / facet (dB) | Propagation loss ($dB.cm^{-1}$) |
|---|---|---|---|---|---|
| A | 4.0 | 5.9 ± 0.1 | 0.06 | 1.5 ± 0.2 | 1.2 ± 0.2 |
| B | 5.0 | 4.0 ± 0.1 | 0.18 | 0.2 ± 0.2 | 1.5 ± 0.2 |

Figures 4(a) and 4(b) are transmission mode optical micrographs of the end facet of the optimum waveguide. Figure 4(a) was acquired by imaging slightly inside the sample whereas Fig. 4(b) was acquired by imaging directly on the waveguide facet surface. Figures 4(c) and 4(d) are near field images of the 1.55 μm mode guided by the optimum waveguide and Corning SMF-28 fiber respectively. Unfortunately, the surface cracking clearly evident in Fig. 4(b) distorts the near field image of the waveguide mode making any sensible quantitative measurements of its dimensions impossible. A visual comparison of the waveguide and fiber

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modes confirms however that the fiber and waveguide modes are reasonably well matched spatially, thus facilitating the low coupling losses measured for this waveguide. Based on the micrograph shown in Fig. 4(a) we estimate that the dimensions of the cross section of the optimum waveguide are ≈ 13 µm x 11 µm in the z- and x-axis respectively, reasonably close to the 8.2 µm core size of Corning SMF-28. Furthermore, it is clear from the low fiber-waveguide coupling losses measured for the optimum waveguide and the near field images presented in Figs. 4(c) and 4(d) that the modes of the optimum waveguide and Corning SMF-28 fiber are well matched spatially. Consequently we conclude that the refractive index contrast of the optimum waveguide is comparable to the 0.36 % refractive index contrast of Corning SMF-28 [16]. It is important to note that the distortion observed in the waveguide mode due to the cracking will be almost negligible when index matching gel is used between the coupling fibers and the waveguide. Consequently, we do not believe that the surface cracking induced a significant increase in the measured IL's.

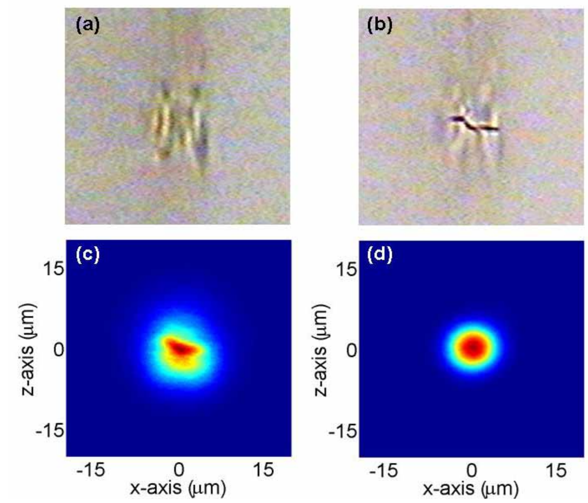


Fig. 4. (a) (b) Transmission mode optical micrographs of the end facet of the optimum waveguide. The images were acquired by imaging (a) slightly inside and (b) directly on the facet surface. (c) (d) Near field images of the 1.55 µm mode guided by the optimum waveguide and Corning SMF-28 fiber respectively. The field of view of each image is 40.0 µm × 40.0 µm.

## 6. Conclusions

We have presented a study demonstrating that a two-dimensional deformable mirror can be used to shape the cross section of ultrafast laser inscribed waveguides. This demonstration could have a significant impact on the ultrafast laser inscription field, potentially enabling the cross section of inscribed structures to be controlled and varied, regardless of the sample translation direction and inscription depth. Future work will focus on optimizing the use of the deformable mirror for this application and on synchronizing the beam shaping with the sample translation.

### Acknowledgments

This work was funded by the UK Engineering and Physical Sciences Research Council (EPSRC) and the Leverhulme Trust under award F00276E.