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# Study of the influence of femtosecond laser polarisation on direct writing of waveguides

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**Abstract:** Optical devices were fabricated in fused silica using the femtosecond direct write technique. We found that the transmission of light through directly written waveguides, whether straight or curved, can be increased by writing waveguides using circularly rather than linearly polarised radiation.

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**OCIS codes:** (320.7130) Ultrafast processes in condensed matter, including semiconductors; (220.4000) Microstructure fabrication; (230.7370) Waveguides

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## 1. Introduction

With the goal of fabricating photonic devices for optical networking applications, significant attention has recently been directed to the use of femtosecond laser pulses for inscribing optical components inside transparent materials. In particular, it has been demonstrated that tightly

focussed femtosecond Ti:sapphire laser pulses can induce a change in the local refractive index inside bulk glasses [1]. The material surrounding the focal volume remains unaffected by the writing laser passing through it allowing structures to be written at arbitrary depths and in a 3D fashion. Optical waveguide structures [2] and both 2-D [3, 4] and 3D [5] optical devices have already been realised in various bulk media. Thus the direct write technique is well suited to the rapid fabrication of photonic integrated circuitry. Another key advantage of the direct write technique is that the glass sample is essentially a self contained clean room offering device fabrication without the need for a controlled environment. These devices are also tolerant to changing environmental conditions by virtue of their being embedded in a bulk material.

Recently it has been shown that optical waveguides written in fused silica using the direct write technique contain polarisation-dependent nanocracks or nanoporous structures [6, 7]. These nanostructures were found to be self-ordered and periodic (with a size and period as low as 20 nm and 140 nm respectively) while being orientated in a perpendicular direction to the electric field vector of a linearly polarised writing beam. These embedded oxygen-depleted periodic structures were visualised using a scanning electron microscope (SEM), Auger electron spectroscopy techniques and selective chemical etching. Two explanations for the formation of these nanostructures have been postulated. Shimotsuma *et al.* argue that the interference between the incident light field and the electric field of the bulk electron plasma wave results in a periodic modulation of electron plasma concentration and permanent structural changes in the glass network [6]. Hnatovsky *et al.* suggest the evolution of nanoplasmas into disc shaped structures due to high non-linear ionisation creates the nanostructures [7].

A quite different modification morphology, however, is produced with circularly polarised femtosecond radiation [7]. Instead of the self-ordered nanostructures typical of linear polarisation, circular polarisation produces embedded disordered nanostructures that vary in size. This result led us to investigate the effect of laser writing beam polarisation on the propagation losses of femtosecond laser written optical waveguides in bulk fused silica. This study coincides with similar, complementary work by Nejadmalayeri *et al.* [8] who investigate waveguides written with circularly polarised light in crystalline lithium niobate. Our work, which is concerned with effects in an amorphous glass, uses circular polarisation and two linear polarisations (parallel and perpendicular to the direction of sample translation) of the writing beam to fabricate straight and curved waveguides. We also compare and contrast, for the first time, the effects that writing polarisation has on the optical transmission of light through such devices.

## 2. Experimental Setup

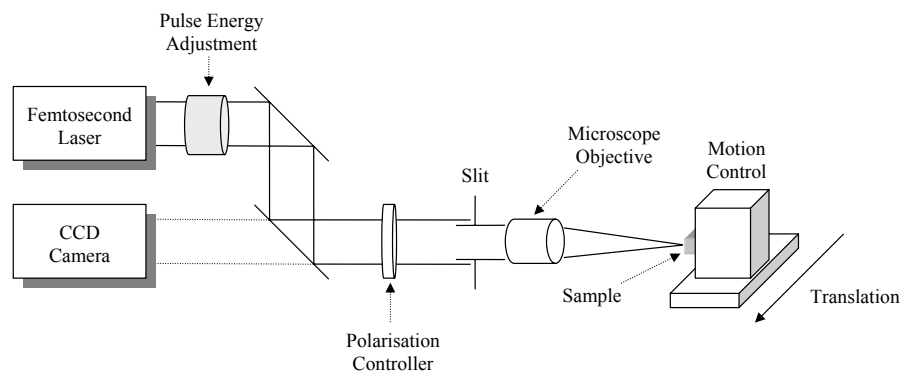


Fig. 1. Writing setup used to fabricate optical waveguides.

The experimental setup is shown in Fig. 1. Optical waveguides were fabricated using a regeneratively amplified, low-repetition rate Ti:sapphire femtosecond laser system (Hurricane) from Spectra-Physics. This system produces  $< 120$  fs, 1 kHz pulses and can deliver an average power of 1 W. Laser pulses at 800 nm were focussed through a  $20\times$  microscope objective (Olympus UMPlanFL, NA 0.46) and injected into polished  $30\times 15\times 3$  mm high-grade fused silica glass samples from Schott (Lithosil Q0).

Before entering the microscope objective, the polarisation of the laser beam was adjusted using a Berek compensator (New Focus Model 5540) and the physical shape of the laser beam was modified by a  $500\ \mu\text{m}$  horizontal slit aperture. The slit (which was orientated with its long dimension in the direction of sample translation) served to expand the laser focus in the direction normal to the laser beam propagation and sample translation. This enabled waveguides with circular symmetry to be written using a low magnification long working distance objective [9].

The beam exiting the femtosecond laser passed through an automated rotatable 1/2-wave plate and linear polariser, allowing fine control of the pulse energy to be achieved. Pulse energies ranging from  $0.5\text{--}10\ \mu\text{J}$ , measured after passing through the slit and before focussing, were used in the formation of optical waveguides. Using a computer controlled XYZ stage (Aerotech FA-130), samples were scanned in a direction  $S$  perpendicular to the direction of beam propagation  $k$ , at a speed of  $25\ \mu\text{m/s}$ .

In order to characterise the fabricated waveguides, a fibre alignment stage was used to position a single mode probe fibre on the structure of interest. The near-field optical mode profiles of the waveguide structures were obtained using a 1535 nm probe and a lens coupled to an IR beam profiler. A measurement of the mode profile was used with a computational method [10] to estimate the peak refractive index change between the bulk material and the waveguide structures. Images of fabricated waveguides were taken with an Olympus differential interference contrast (DIC) microscope. The transmitted 1535 nm radiation was collected using an aligned single mode fibre coupled to a power meter.

### 3. Results and Discussion

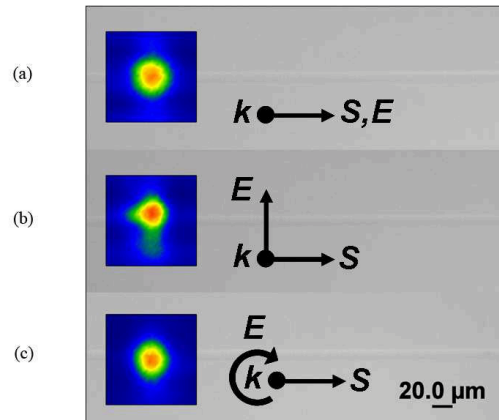


Fig. 2. Differential Interference Contrast (DIC) microscope images of waveguides fabricated in fused silica using (a) linear parallel polarisation (b) linear perpendicular polarisation and (c) circular polarisation. The  $k$ -direction of the laser beam propagation,  $S$ -direction of sample translation and  $E$ -electric field vector are also shown. Insets show the near-field profile corresponding to each waveguide. The direction of the writing beam with respect to the insets was from top to bottom.

Optical waveguides were fabricated in fused silica using three different states of polarisation of the writing beam. Example DIC microscope images of a sample of these waveguides (viewed from above) written with an incident pulse energy of  $3.5 \mu\text{J}$  are shown in Fig. 2. The corresponding near-field profiles of these waveguides are shown in the insets respectively. The approximate diameters of the waveguides are  $10 \mu\text{m}$ . Using the near-field profiles shown in Fig. 2, a refractive index contrast of  $8.9 \times 10^{-4}$ ,  $1.2 \times 10^{-3}$  and  $1.7 \times 10^{-3}$  was calculated for linear parallel, linear perpendicular and circular polarisations respectively. As these three waveguides have approximately the same core size but differ in index contrast, the guided mode is expected to be more tightly confined in waveguides written with circularly polarised femtosecond radiation.

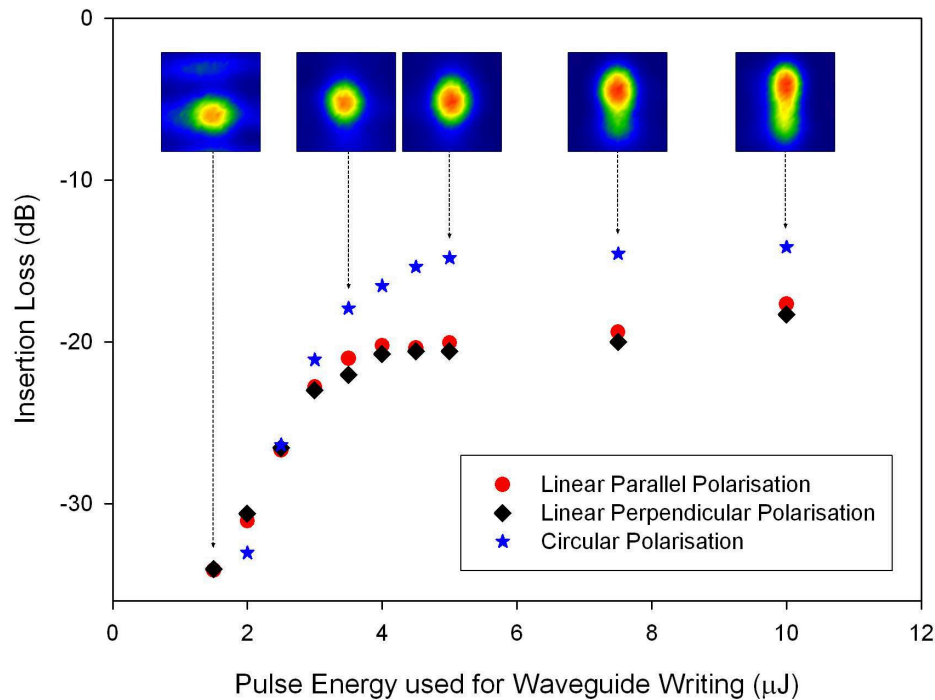


Fig. 3. Insertion loss measured at 1535 nm for waveguides fabricated with various writing beam pulse energies and polarisations. Insets show near-field profiles of waveguides fabricated with corresponding energies. The direction of the writing beam with respect to the insets was from top to bottom.

The optical transmission of 1535 nm light through a range of waveguides fabricated using a fixed slit width and various pulse energies and polarisations is shown in Fig. 3. For the case of linearly polarised radiation, the optical transmission was similar when the electric field vector of the writing beam lay either parallel or perpendicular to the direction of sample translation. Clearly, the optical transmission of light through a direct written waveguide can be increased by fabricating waveguides using circularly polarised femtosecond radiation. In fact, the absolute optical transmission increased by a factor of 3 at a pulse writing energy of  $5 \mu\text{J}$ . Beyond this value the transmission through a waveguide increases at a reduced rate as a function of pulse energy. We attribute this observation to the waveguides becoming asymmetric and multimode. This waveguide core asymmetry at high fabrication pulse energies can be seen by noting the near-field profiles shown in Fig. 3. The elongated structures are a direct result of self-focussing

of the writing beam due to Kerr lensing at high pulse energies. However, in an earlier body of work [9], we showed that the waveguide asymmetry caused by these self-focussing effects can be compensated for by adjustment of the slit width  $W_y$ . In particular, we derived the following equation which governs the aspect ratio of the slit,  $\frac{W_y}{W_x}$ , required to fabricate waveguides with symmetrically shaped cross-sections:

$$\frac{W_y}{W_x} = \frac{NA}{n} \sqrt{\frac{\ln 2}{3}} \quad \text{for } W_x > 3W_y. \quad (1)$$

NA is the numerical aperture of the focussing objective,  $n$  the refractive index of the glass substrate and  $W_x$  the unapertured beam waist.

A propagation loss study was performed using six different types of fabricated waveguides. For a fixed pulse energy of  $3.5 \mu\text{J}$  we fabricated a waveguide using linear perpendicular and circular polarisations, a waveguide overwritten 8 times with the same pulse energy again using linear perpendicular and circular polarisations, a waveguide using  $45^\circ$  linearly polarised light and a waveguide using  $45^\circ$  elliptically polarised light with a major to minor axis ratio of 2:1. The propagation loss of these 6 waveguides are shown in Table 1.

Table 1. Propagation losses for a variety of directly written waveguides. Polarisation angle is relative to the direction of sample translation.

Polarisation Type	Polarisation Angle	Fabrication Scans	Propagation loss
Linear	$90^\circ$	1	1.75 dB/cm
Linear	$90^\circ$	8	0.52 dB/cm
Linear	$45^\circ$	1	1.9 dB/cm
Elliptical	$45^\circ$	1	1.65 dB/cm
Circular	-	1	0.83 dB/cm
Circular	-	8	0.36 dB/cm

Once again our results show that the lowest loss waveguides are fabricated using circularly polarised light. This loss decreases when the multiple pass technique is employed. The single pass linearly polarised written waveguides exhibit similar propagation losses. The propagation loss of the elliptically written waveguide was between that of the linearly and circularly polarised written waveguides as expected.

We believe the relatively high propagation losses associated with waveguides fabricated using linearly polarised radiation is related to the underlying mechanism that produces the periodic nanostructures identified by Shimotsuma *et al.* and Hnatovsky *et al.*. This relationship is consistent with the improved propagation loss of the waveguides written with circularly polarised light and the reduced presence of these periodically aligned nanostructures noted in [7] when circular polarisation is used. However, further study is required to firmly establish this link between these two independent investigations.

In a follow up qualitative study we investigated the influence of laser polarisation on bend losses. The curved waveguide device shown in Fig. 4 was fabricated using each of the three states of polarisation outlined above. The waveguide consisted of a shallow bend with radius 55 cm over a length of 15 mm giving an output deviation of 0.15 mm from the optical axis of the input beam. To help facilitate the visual monitoring of bend losses, single mode curved waveguides were fabricated for use at 635 nm.

We measured similar transmissions for the curved waveguides fabricated using both states of linear polarisation. The curved waveguide fabricated using circularly polarised radiation

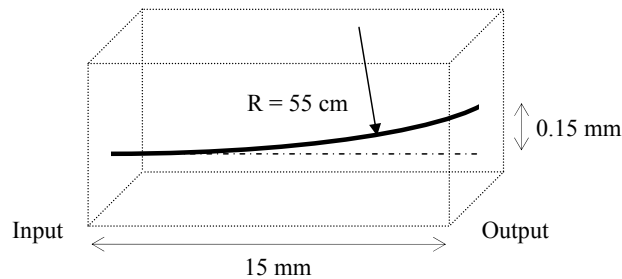


Fig. 4. Schematic of the curved waveguide fabricated in fused silica using various writing beam polarisations.

resulted in a throughput approximately 3 times greater than the value achieved for the linearly polarised written curves. These results are consistent with those shown in Fig. 3 for the case where straight waveguides were written with three different states of polarisation.

In these studies of bend losses the resulting tangent between the input and output axes was approximately  $1^\circ$ . Writing curved waveguides with greater angles and a fixed slit orientation would lead to asymmetries in the waveguide cross-section. To mitigate this effect the long axis of the slit can be synchronously rotated as a function of waveguide angle. An alternative methodology is to use MHz laser systems without the optical slit where cumulative heating effects automatically generate circular waveguide cross-sections [11].

Importantly, we have shown that there are clear device advantages to using a circularly polarised femtosecond writing beam when fabricating curved waveguides with a kHz laser system. At this stage it is not clear whether the same advantages apply to straight or curved waveguides written using a MHz laser system.

#### 4. Conclusion

Optical waveguide devices were fabricated in fused silica glass using three states of polarisation of a focussed femtosecond laser beam. We compared and contrasted, for the first time, the optical transmission properties of straight and curved waveguides written with linearly and circularly polarised light, and show an increase in transmission through waveguides written using circularly polarised light. This increase in light transmission is still under investigation but may be explained by a modification of the periodic *aligned* nanostructures that accompany devices fabricated with linearly polarised radiation. The use of long working distance objectives and circularly polarised femtosecond laser beams for modifying bulk materials offers simplicity and opens new possibilities for the fabrication of passive and active integrated optics and compact 3D optical circuits.

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