Femtosecond Written Silica Waveguides for High Extinction Polarization Filtering

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Abstract: Silica waveguides with polarization-selective transmission were written by femtosecond laser inscription using linear and circular polarization. By tailoring writing parameters, polarization-dependent losses from 0.5 to 24dB at 1310nm were achieved.
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The last decade has seen growing research and industrial interest towards femtosecond writing, which relies on focusing high power pulses into a substrate where nonlinear absorption effects localized at the focal volume result in a permanent refractive index modification [1]. Thus, complex 3D structures can be rapidly designed, implemented and tested, such as waveguides, gratings and multiplexers [2-4]. To expand the scope, additional functionality for signal processing or filtering is important.

We report here on the fabrication and demonstration of waveguides with polarization dependent transmission, i.e. which transmit one polarization well but strongly attenuate the other. The geometry is a straightforward step-index buried waveguide, which allows easy and compact incorporation with integrated optics for applications necessitating polarization filtering, such as sensing or polarization division demultiplexing signal cleaning.

Waveguides were inscribed using 1030 nm wavelength 200 fs pulses from a Pharos 05-200-PP laser (Light Conversion Ltd., Lithuania) focused by an objective (Leitz Wetzlar ×25 0.4NA PLAN), as shown in Fig. 1. The first half-waveplate and polarizing beamsplitter cube control power, while a second half-waveplate adjusts polarization angle. Both linear and circular polarization writing beams were investigated; the latter by inserting a quarter-waveplate before the objective. The multiscan method [2] was used to create 10 µm wide waveguides by scanning 50 lines spaced 200 nm apart. All waveguides were 10 mm long and inscribed 500 µm beneath the surface, in fused silica substrates (Spectrosil 2000, Heraeus). After writing, both ends were lapped to expose the facets and polished.

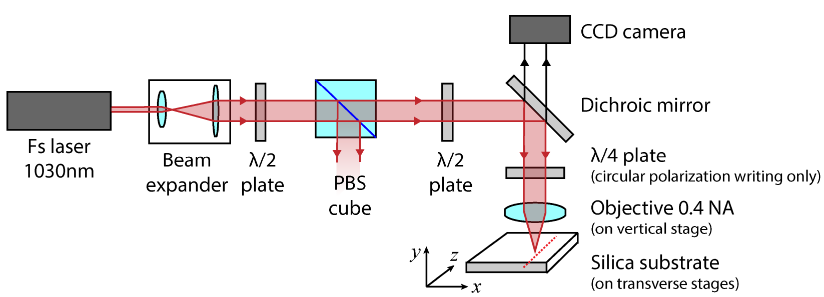

Fig. 1. Femtosecond writing set up for fabricating waveguides. The *x* and *y* axes are transverse to the waveguide direction *z*, and the writing beam is aligned with the *y* axis.

The objective and sample are both mounted on precision translation stages (Aerotech Ltd.) and the laser pulse firing is synchronized to the sample position. Thus, the pulse density D, i.e. number of pulses per mm along the waveguide, can be conveniently adjusted independently of writing velocity v. In addition, the pulse burst k_B can be set so the laser fires multiple times at each point. For example, $D = 10^4$ mm^{-1} with $k_B = 3$ implies that every 100 nm, the laser will fire 3 pulses (in the same spot). The product $D{\cdot}k_B{\cdot}v$ cannot exceed the laser maximum repetition rate of 200 kHz. Note that this relatively low pulse frequency means no significant cumulative heating is observed [5].

To characterize the waveguides, CW light from a 1310 nm laser diode was launched into a linear polarizer and half-waveplate to control polarization, before being butt-coupled via polarization maintaining (PM) fiber into the waveguide. The output was focused by a 0.6 NA objective onto either a CCD or power meter, for mode field diameter (MFD) or loss measurements, respectively.

All waveguides were written with a 10×10 µm square cross-section core as shown in Fig. 2(a), and in each case, the *y* polarization was found to transmit better than the *x* polarization which experienced scattering. Examples of the transmitted *y* polarized mode intensity profile are given in Fig. 2(b) and (c).

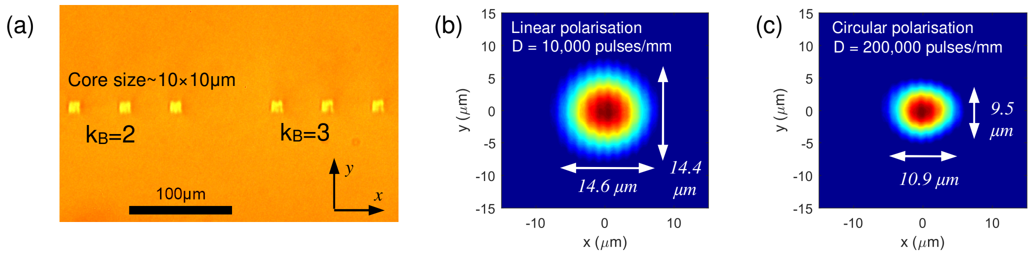

Fig. 2. (a) Microscope image of waveguide cross sections, written by linear polarisation for $k_B = 2$ and 3. (b) *y*-polarised mode intensity profile for $D = 1\times10^4$ pulses/mm written using linear polarisation and (c) $D = 2\times10^5$ pulses/mm using circular polarisation. The $1/e^2$ MFD is labelled.

For a writing beam linearly polarized perpendicular to waveguide direction, Fig. 3(a) shows that as pulse density increases from 5000 to 15000 pulses/mm (while keeping velocity constant at 5 mm/s and pulse energy at 300 nJ), the *y* polarized mode loss remains low in the range α_y = 1.2–1.5 dB, whereas the *x* polarization loss increases steeply from α_x = 1.6 to 13.0 dB due to increased scattering. The scattering is believed to arise from the presence of anisotropic nanostructures [1, 6] formed under higher pulse density regimes, which can be adjusted to engineer a desired extinction ratio between the transmitted and scattered polarization. Thus, the polarization dependent loss (PDL) increases from only 0.5 up to 11.5 dB. Likewise, increasing k_B from 1 to 4 causes a similar effect shown in Fig. 3(b) with PDL reaching 12.7 dB, while α_y is kept small in the range 1.3–2.1 dB.

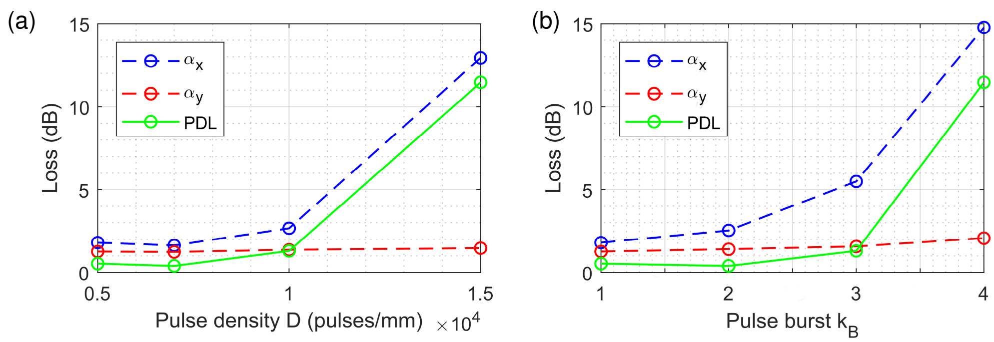

Fig. 3. Waveguide insertion loss measured with *x* and *y* polarizations and polarization-dependent loss against (a) writing pulse density, with $k_B = 1$ and (b) pulse burst, with D = 5000 pulses/mm. Written with perpendicular linear polarisation at velocity of 5 mm/s. Note: insertion loss values include fibre-waveguide coupling loss and Fresnel reflection loss.

Increasing either D or k_B beyond these ranges results in damage and high loss for both polarizations. However, writing with circular polarization allows much higher pulse densities to be tolerated. For D = 200,000 pulses/mm (v=1 mm/s, k_B=1 and pulse energy at 300 nJ), the waveguide losses are α_y = 2.5 dB and α_x = 26.8 dB, thus achieving a high PDL of 24.3 dB. These waveguides are well suited for polarization filtering requiring high extinction.

In conclusion, waveguides which selectively transmit the *y* polarization and filter out the *x* polarization, with an extinction up to 24 dB at 1310 nm, were fabricated by femtosecond writing at 1030 nm. Both linear and circular writing polarizations were investigated, with circular polarization offering higher extinction. The mechanism relies on a polarization dependent scattering effect enhanced by writing at higher pulse densities of 10^4–10^5 pulses/mm.

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