Composite Morphology Laser Written 3D Waveguides with Reduced Bend Loss

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Abstract: We demonstrate a composite laser written 3D waveguide in boro-aluminosilicate glass, with an estimated index contrast of 1.7%, providing a 2.5x improvement of minimum bend radius down to 4.0 mm at 1550 nm.

1. Introduction

As the field of integrated photonics continues to mature, there is ever greater demand for increased integration, which is essential for enabling future network components such high connection density interconnects for multi-core optical fibres and silicon photonics, as well as quantum computational circuits. The Femtosecond Laser Direct Write (FLDW) technique entails the precisely controlled translation of suitable glass and polymer substrates through a focused femtosecond pulsed laser beam which induces a localised permanent refractive index change in the focal volume. The platform allows for the fabrication of low-loss, polarisation insensitive 3D waveguide circuits in a scalable and low-cost fashion. The platform is also well suited to rapid prototyping due to the absence of any requirements for lithographic masks. The capabilities of FLDW support the field of Spatial Division Multiplexing (SDM), facilitating, for example, compact and low-loss multi-core fibre fan-outs. Due to the 3D capability, diverse waveguide remapping geometries are possible, enabling coupling to multi-core fibres with large numbers of cores or with arbitrary, non-circular core layouts. Low loss mode selective couplers with high modal purity can be integrated directly into the fan-out waveguide geometry, enabling interfacing with few-mode optical fibre, and indeed, few-mode multi-core fibres. This has facilitated the demonstration of a 1 petabit per second SDM switching node [1]. Laser written waveguides typically feature low-refractive index contrast, on the order of 10^{-3}. Refractive index contrast governs the confinement of the optical mode and dictates the minimum radius of waveguide curvature. This is one of the most significant design limitations for any photonic integrated circuit, as it directly constrains component density and device footprint. With respect to SDM, this limits the number of practically addressable spatial channels, since larger bend radii necessitate larger path-lengths, which in turn incur larger loss penalties. Various approaches to improving the index contrast of FLDW waveguides have been reported over the years, including laser-induced electronic band-gap shift to exploit electronic resonances [2], thermal annealing [3], tuning the composition of the substrate glass [4], waveguide-air interfaces [5] and damage induced stress fields [6]. In this work, we demonstrate a non-damaging approach based on a novel multi-pass ultra fast laser written waveguide, fabricated in boro-aluminosilicate glass. The technique involves two sequential fabrication steps, one carried out in the cumulative heating (high pulse repetition rate) and the second in the athermal (low pulse repetition rate) regime, respectively. This produces a composite morphology waveguide which additively combines the respective mechanisms of material modification, yielding a 2.5x reduction of the minimum bend radius, from the previous record of 10 mm at 1550nm [7], to 4 mm. The index contrast is estimated to be 1.7%.

2. Cumulative Heating Modification

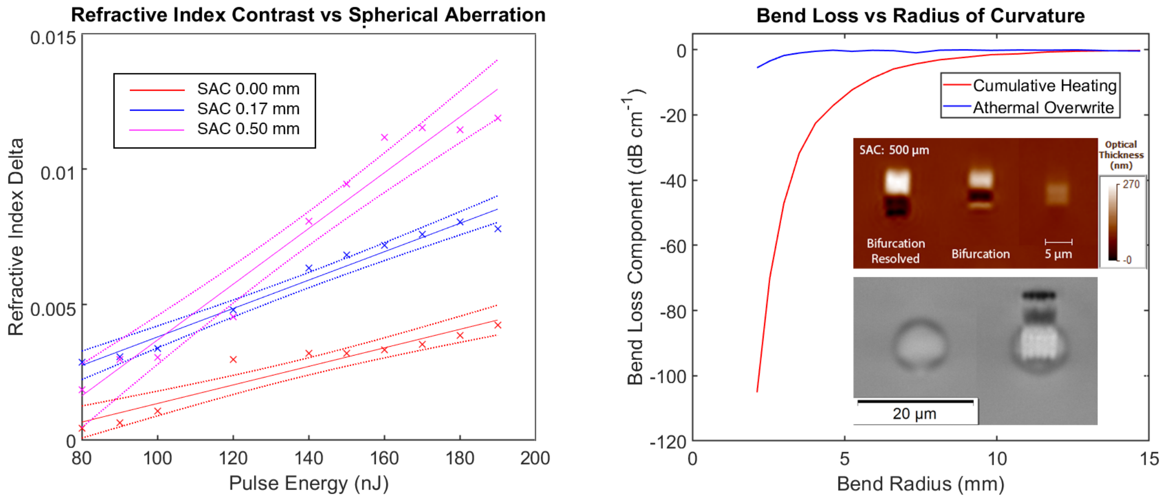
Integrated optical waveguides were fabricated in Corning Eagle XG glass at a depth of 250 μm, using a Ti:SPh femtosecond pulsed laser (Femtosource XL500, Femtolasers GmbH) operating at 800 nm, with a pulse duration of 50 fs. The beam was focused into the glass using an Olympus UPLANSAPO 100× oil immersion microscope objective, with a numerical aperture of 1.4. The waveguides were inscribed with a high pulse repetition rate (5.1 MHz), which causes the diffusion of heavier elements into the center of the focal volume, changing the local composition and density of the substrate glass [8]. Cumulative heating waveguides are preferable in boroaluminosilicate glasses for their high index contrast, low linear propagation losses, rapid fabrication speed (up to 2000 mm/min) and the circularity of their morphology and guided mode field, which enable efficient coupling to standard single-mode optical fibres.

3. Athermal Modification

Athermal modification was achieved by reducing the laser's pulse repetition rate using an electro-optic pulse picker. In this regime, the refractive index change arises from an increase in the local stress, and the density of 3- and 4- member silicon-oxygen rings [9]. The beam was focused with an Olympus LUCPlanFLN 40x air objective. The region of modification is constrained by focusing conditions and is typically on the order of 0.2 to 0.4 μm in width. Multi-scan waveguides can be constructed by raster-scanning the beam. Additionally, by controlling the order inscription according to the Half-Scan algorithm, it is possible to evenly distribute local stress fields, resulting in a uniform modification [10]. An extensive parametric study of athermal writing parameters was carried out to optimise for morphology and index contrast.

3.1. Half-Scan Modification Parametric Study

The morphological and guiding properties of a half-scan waveguide are determined by several fabrication parameters: pulse energy, pulses per mm, pulse repetition rate and spherical aberration compensation. It was observed from iterative testing that index contrast scales with pulse density, and inversely with pulse repetition rate. Hence, pulse density and repetition rate were fixed at 200,000 pulses per mm, and 150 KHz, respectively.



(a) (b)

Fig. 1: a) Experimental measurement of peak refractive index contrast as a function of inscription pulse energy for different spherical aberration compensation regimes. b) Waveguide bend loss for both standard cumulative heating, and composite waveguides. The upper inset shows a quantitative phase image of three athermal waveguides. The left and right waveguides were inscribed with high and low pulse energy, respectively. The center waveguide illustrates the bifurcation phenomenon encountered in the intermediate range. The lower inset shows bright field microscope images of a cumulative heating waveguide before and after athermal overwriting.

Waveguide morphology and index contrast were examined as functions of pulse energy and spherical aberration. A positive linear relationship was observed between pulse energy and index contrast (Figure 1-a), however, above a certain threshold, the region of positive index change undergoes horizontal bifurcation, and a region of negative index change forms between the two lobes (this is shown in Figure 1-b's inset). This is problematic, since it would create complex guidance conditions subject to multi-mode interference. When the Spherical Aberration Correction collar (SAC) of the focusing objective is set to 0.00 and 0.17 mm, the bifurcation threshold caps off the useful-morphology index contrast at 3.0×10^{-3}. Setting the SAC to 0.50 mm, however, yields an interesting change in this behaviour. As the bifurcation threshold (110-120 nJ) is crossed, the morphology initially splits, however, as pulse energy is further increased, the bifurcation effect diminishes, resulting in a single strong region of positive index change, situated below a region of strong negative index change (Figure 1-b's inset). While the presence of the negative region will serve to slightly compress the guided mode field in the vertical axis, peak index contrast is no longer bound by the bifurcation limit. As a result, a peak index contrast of 1.2×10^{-2} is now accessible.

4. Multipass Composite Waveguide Experiment

Cumulative heating waveguides were fabricated with a feed-rate of 1500 mm/min and a pre-annealed width of 30 μm. The cores of straight waveguides were overwritten with optimised half-scan segments. The linear propagation losses of the composite waveguides where measured by fabricating waveguides with different lengths of athermal segments, ranging from 2 to 8 mm. The half-scan segments also feature 3 mm long linear tapers at their terminations, in order to create a smooth transition. At 1550 nm, the linear propagation loss was measured to be 0.5 dB cm^{-1}. The half-scan modifications incur a loss penalty of 0.12 to 0.22 dB per tapered termination, which may be reduced with further optimisation. Cumulative heating waveguides featuring S-bends comprised of two concatenated circular arcs spanning a fixed side step of 500 μm were fabricated. The bend radius was iterated from 32.1 mm to 2.1 mm by varying the length of the S-bend. For bend radii larger than 11.0 mm, conventional cumulative heating waveguides provide superior throughput. Togther with taper transition loss of 0.44 dB, the purely bend-induced loss component can be extracted as shown in Figure 1-b. The -1.0 dB cm^{-1} cut-off radius for standard low-loss cumulative heating waveguides was approximately 11 mm. The multi-pass technique reduced this to 4 mm when aggregating the propagation loss component and the bend loss component, or 3.5 mm when considering only the bend loss. Based on addition of the respective index contrast contributions, 0.5% for cumulative heating waveguide and 1.2% for the athermal modification, the estimated index contrast of the composite waveguide is 1.7%.

5. Conclusion

The multi-pass approach to integrated waveguide fabrication additively combines the refractive index modifications of both the cumulative heating and athermal inscription regimes. The result is a dramatic reduction of the bend losses which lead to a reduction of the 1.0 dB cm^{-1} cut-off radius to 4 mm. This represents a 2.5x improvement of the state of the art, from a previously reported 10 mm radius for 1550 nm, based on laser induced micro-cracks [7], facilitating more compact photonic circuits.

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