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Prospects for ultrafast-laser writing of three-dimensional photonic devices for Telecom applications

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Abstract: We present results of the first optical characterization at Telecommunication wavelengths of glass waveguide structures formed with ultrafast lasers. Waveguide losses of ~1.5 dB/cm and refractive index changes of up to 10^{-2} are noted across a broad spectrum of ~900 to 1620 nm.

OSIC codes: (130.3120) Integrated optics devices; (230.7380) Waveguides, channeled; (320.7120) Ultrafast phenomena

1. Introduction

Ultrafast laser processing offers new prospects to miniaturize and integrate highly functional photonic devices directly inside transparent materials. Nonlinear optical interactions induce strong refractive-index changes in sub-micron volumes that permit the generation of two and three dimensional refractive-index structures with simple motorized translation stages. The ultrafast interaction does not require specially prepared or photosensitive materials and various silica-based components such as passive and active waveguides [1,2] and directional couplers [3] have been reported. Surprisingly, all known reports on waveguide characterization have focused on visible wavelength sources (i.e. ~633nm) even though applications are targeted for Telecom purposes centered at 1.55 μm in the near-infrared spectrum. In this paper, we present the first characterization of ultrafast-laser formed waveguides in the Telecom Spectrum (1520-1620nm) and describe laser-processing windows for generating low-loss, single and multi-mode devices, across a broad spectrum.

2. Experiment

Refractive index structures were written inside optically polished fused-silica blocks (10mm x 10mm x 20mm, UV grade) with a regeneratively amplified Ti^{3+}:Al_2O_3 laser pumped by an Ar^+ laser. The 45-fs duration pulses were applied at 100-kHz repetition rate and 290-mW average power. A focal spot was generated ~500μm below the glass surface using a patented focusing concept. A sub-micron resolution x-y-z stage (Newport, PM500-L) scanned samples transversely to the laser beam, in a side-writing geometry, to form cylindrically symmetric waveguides at various speeds of 5 to 600 μm/s.

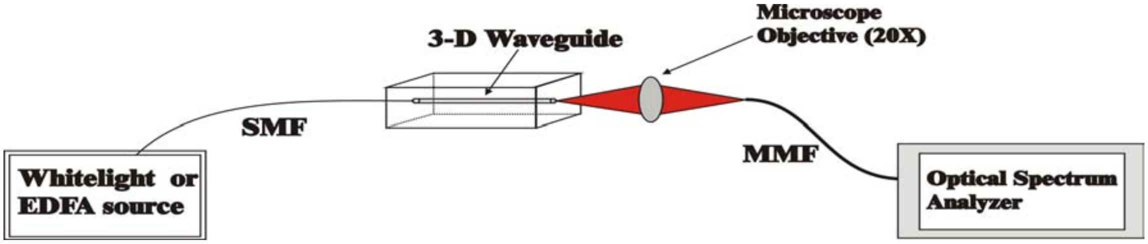
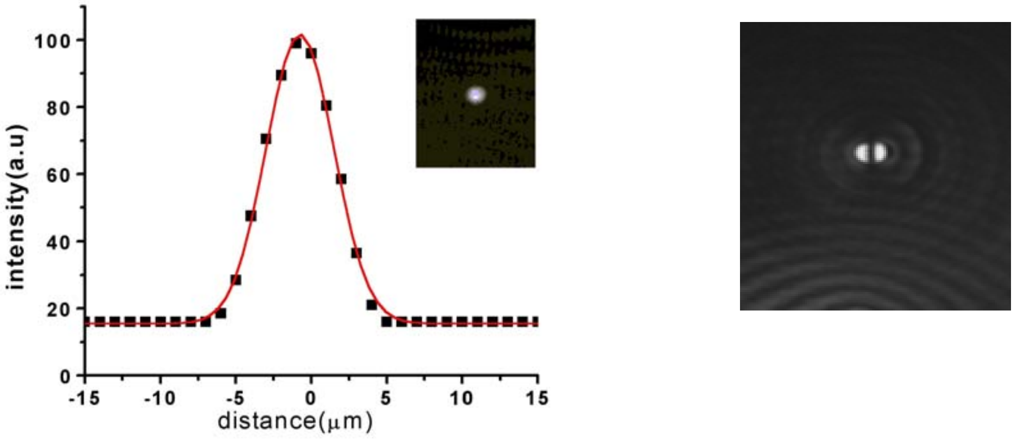


Fig. 1. The experimental arrangement for waveguide characterization. MMF: multimode fiber; SMF: single-mode fiber

Several laser and broad-band sources were applied as shown in Fig. 1 to the waveguide characterization: 635nm laser diode (Thorlabs, S1FC635), 1520-1580 nm tunable laser (Photonetics, Tunics-BT), 1530-1610 nm EDFA (Thorlabs, ASE-FL7002) and 400-1800 nm white light (ANDO, AQ4303B). All sources were available in single-mode fiber (Corning, SMF-28, NA=0.13), which was butt-coupled to the ultrafast laser-generated waveguide using precision translation stages. Waveguided output light was collected with a 20X microscope objective, imaged into a multimode fiber (MMF, 500-µm core, Polymicro, FIP500550) and processed by an optical spectrum analyzer (ANDO, AQ 6317B). In another configuration, a near-field image of the guided light mode profile was captured with an IR camera (Coherent, E-7290) positioned at the MMF input facet.

3. Results and discussion

The waveguide properties were varied by controlling the waveguide writing speed, the ultrafast laser power and the laser focusing geometry. Fundamental or higher-order modes could be selected by tuning the probing wavelength or adjusting the launch-fiber position with respect to the waveguide. Figure 2a (right) shows the near-field intensity distribution of 1550-nm light leaving a waveguide written at 50µm/s. A Gaussian representation (left) of the cross section reveals single-mode confinement. Figure 2b shows that higher mode guiding is possible in the same waveguide when short-wavelength 635 nm light is launched. Multi-mode behavior was also observed at 1550 nm for waveguides made with a slow writing speed of 10 µm/s. For an estimated waveguide diameter of 4-6 µm, we inferred a maximum refractive index change of 10^{-2} at 1550 nm, with higher values noted for shorter wavelength light.



(a) (b)

Fig. 2. Near-field modal beam profiles for waveguides formed at 10 µm/s: (a) Gaussian representation (left) and profile (inset, right) when probed at 1550 nm; (b) higher-mode profile when probed with 635 nm.

The waveguide insertion loss has contributions from Fresnel losses, the modal mismatch between the coupling fiber and laser-formed waveguide, and scattering and absorption losses within the waveguide. Fig. 3a shows Telecom-band transmission spectra of waveguides formed at different writing speeds and a reference spectrum of the EDFA source. The slowest writing speed (5µm/s) offered the lowest insertion loss of 12 dB. Waveguides were further probed over a broad 850-1600 nm spectrum (2-nm resolution) as shown in Fig. 3b. In all cases, losses were not wavelength dependent and therefore could not be ascribed to glass defects such as Si-OH centers. BPM CAD (Optiwave) codes were applied to estimate the mode-mismatch loss for fiber butt coupling for various values of waveguide refractive index change. Correlations with the writing-speed-dependent losses in data like Fig. 3 suggest that a laser-induced index change of $0.8\text{x}10^{-3}$ to $10\text{x}10^{-3}$ was generated for scan speeds of 600 to 10 µm/s, respectively. To determine the intrinsic waveguide loss (absorption and scattering), waveguides of 10-mm and 20-mm length were generated at various scanning speeds and characterized for insertion losses at 1550 nm. Waveguide losses varied from 1.5 to 6 dB/cm and were smallest at a 200 µm/s scan speed. Moderately low-loss directional couplers and Y-splitters were further fabricated for 1550 nm operation with the optimum laser conditions explored above. With further optimization, ultrafast lasers are promising sources for writing Telecom-quality optical waveguide components. Recent work [4,5] suggest that much faster waveguide writing speeds of 1 to 10 mm/s might be available when using multi-MHz rate ultrafast lasers.

4. Conclusions

We demonstrate for the first time that ultrafast lasers can fabricate low-loss three-dimensional photonic devices in bulk glass for operation in the Telecom spectral band pf ~1550 nm. Refractive index changes in the attractive range of 10^{-3} to 10^{-2} were generated.

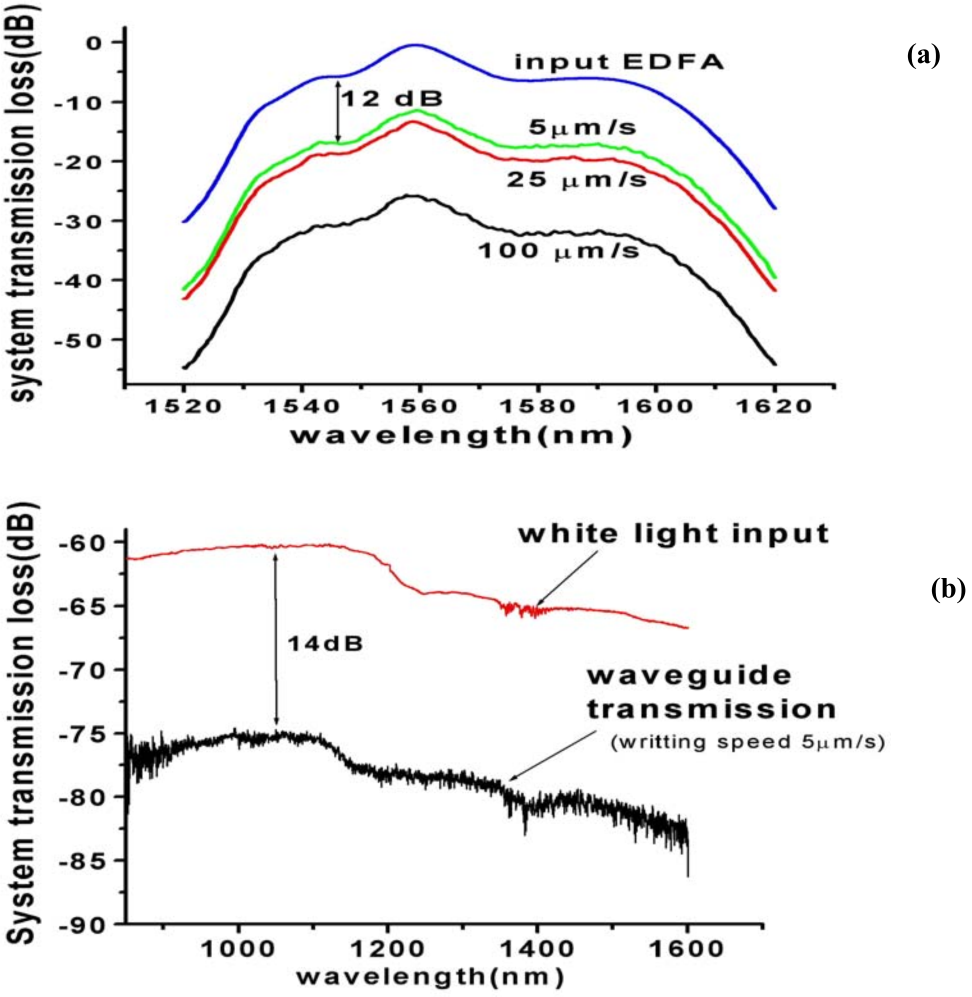


Fig. 3. Transmission spectra of various waveguides probed with an (a) EDFA and a (b) white light source.

5. References:

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