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Optical Circuits in Fiber Cladding: Femtosecond laser-written Bragg Grating Waveguides

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Abstract: High strength, first order Bragg Grating Waveguides are inscribed in the core and cladding of optical fibers using oil immersion femtosecond direct laser-writing. A laser-induced birefringence of $2.05\text{x}10^{-4}$ was inferred from polarization split Bragg resonances.
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1. Introduction

Femtosecond lasers have given access to nonlinear optical interactions that can alter materials in new ways. For optically transparent media, such interactions have opened possibilities in fabricating three-dimensional integrated optical components including waveguides, directional couplers and Bragg Grating Waveguides (BGW) [1] and further extend to 3D optofluidic microsystems by combining optical devices with laser-generated microfluidic channels. While these laser-written devices promise to expand the component toolkit for fabricating highly functional three-dimensional integrated optical circuits, their integration in the cladding of a single-mode optical fiber represents a highly attractive extension of this technology for new types of compact optical communication and sensing devices including lab-on-a-fiber concepts. Many laser approaches, including femtosecond direct laser-writing, have been developed for writing Bragg gratings into the pre-existing core of optical fibers [2]. In this paper, we extend our method of fs-laser BGW writing to report on high strength, first order BGW in both the core and cladding of a SMF-28 fiber. Prospects of creating 3D optical circuits within the optical fiber will be discussed.

2. Femtosecond Laser Writing Arrangement

To fabricate the BGWs, a Yb-doped fiber chirped pulse amplified femtosecond laser (IMRA America; µJewel D-400-VR) with a center wavelength of 1044 nm, 300 fs pulse duration, and operating at a repetition rate of 500 kHz was directed into an acousto-optic modulator to create burst trains of laser pulses that produce a periodic refractive index profile when focused into the sample [1]. The second harmonic (522 nm) output was used to drive stronger interactions that produce stronger guiding waveguides in fused silica [3]. Further, to both drive stronger interaction and avoid extreme spherical and astigmatic optical aberrations, laser pulses were tightly focused by a 100X, 1.25 NA oil-immersion lens into the SMF-28 optical fiber. The fiber was held taught in suspension and aligned with ±1 µm accuracy over a distance of 10 cm permitting long or multiple devices to be fabricated without shifting of the fiber position during exposure. The fiber was mounted on an air-bearing motion stage (Aerotech ABL1000) and translated with respect to the laser beam which was linearly polarized parallel to the direction of motion of the stage. The desired Bragg wavelength was determined according to: $\lambda_B = 2n_{eff}\Lambda$, where λ_B is the reflected Bragg wavelength, n_{eff} is the effective index of the waveguide mode and Λ is the grating period, which was controlled by the ratio of the scan velocity to the AOM modulation frequency. A Bragg resonance of λ_B = 1550 nm was obtained with a scanning speed of 0.268 mm/s and an AOM square-wave modulation of 500 Hz and 60% duty cycle.

The optical characterization followed the fiber coupling procedures previously described in [1]. A separate free-space launching system was also used to independently launch vertical and horizontal linearly polarized light and record the birefringence induced shift in the Bragg resonance. All spectra were recorded with an optical spectrum analyzer at 0.01 nm resolution.

3. Bragg Grating Waveguide Devices

The microscope images in Fig. 1 illustrate the controllable fabrication of BGWs to precise locations either in the in the core or cladding of an SMF-28 fiber. The reflection and transmission spectra, the mode profiles (at 1560 nm) and mode field diameters (MFD) and the birefringence for these BGW devices are shown in Fig. 2 for both the core and cladding positions. The BGWs are single mode at 1560 nm and have approximately circular MFD that are within ±1.4 µm of a single mode fiber (10.4 µm). The peak reflection (1.5 dB), transmission (32 dB) and 3 dB bandwidth (0.2 nm) are similar to those reported in bulk glass [1]. Fig. 2 (b and d) shows the core and cladding devices to have birefringence on the order of 10^{-4}. These birefringence values, decreased with the laser pulse energy and are approximately 3-4 times higher than those obtained using similar laser writing parameters without oil-immersion.

Large cladding mode losses of 3.5 dB (Fig. 2a) for the BGW fabricated in the fiber core may be reduced by testing other focusing arrangements to spread out the index modification while further reduction is possible by keeping the buffer coating on the fiber during the fabrication as in [4]. Otherwise, much lower (<0.8 dB for a 20 mm long grating) insertion loss is found for wavelengths longer than the Bragg resonance. The losses in the BGW written in cladding of the fiber can be further optimized by reducing the pulse energy and considering other focusing geometry.

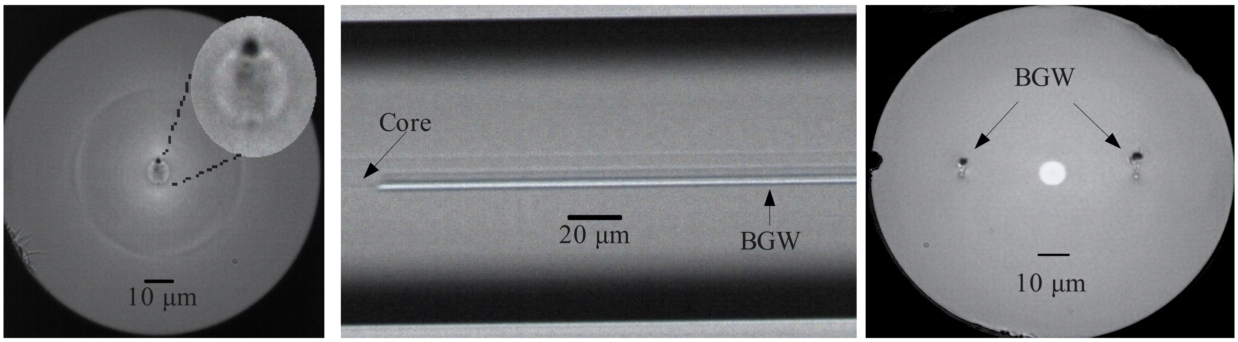

Fig. 1. Microscope images of BGWs fabricated in the core [end-view (left) and side-view (middle)] and cladding (right) of a SMF-28 optical fiber

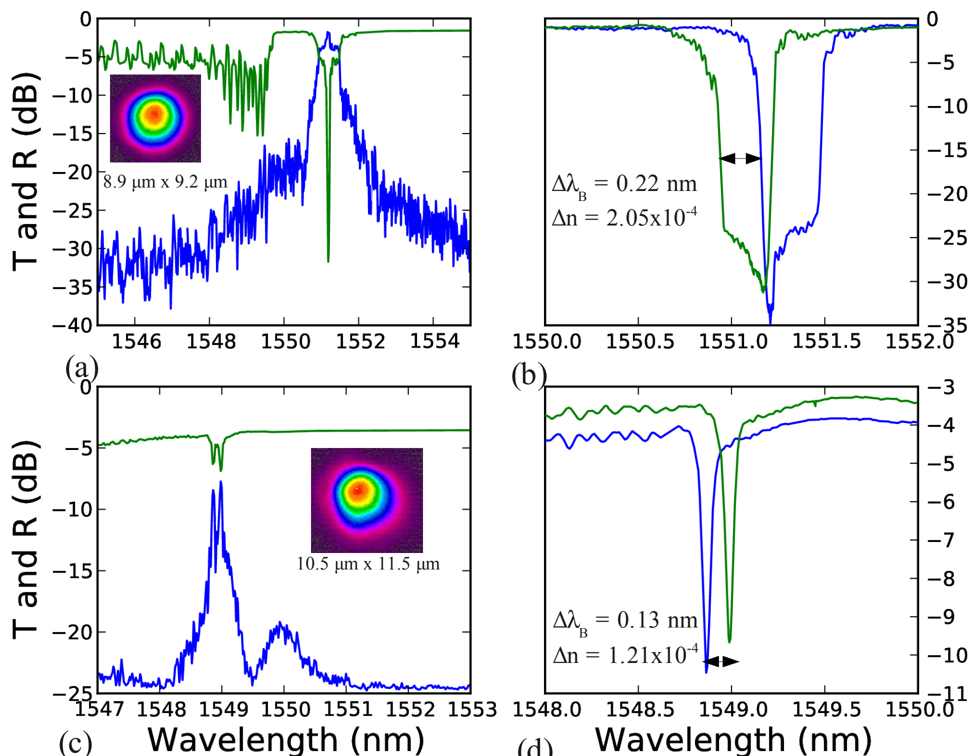

Fig. 2. Spectra and mode profiles of a 20 mm BGW fabricated in the fiber core (a) with 90 nJ pulse energy and in the fiber cladding (c) with 170 nJ pulse energy. The polarized transmission spectra in (b) and (d) for devices in (a) and (c), respectively.

4. Summary

BGWs were fabricated in the core and cladding of an SMF-28 fiber using an oil immersion femtosecond direct laser-writing technique. Induced birefringence up to 2.05x10^{-4} was measured with total insertion losses of 0.8 dB. The fabrication of optical circuit components in the cladding of optical fibers opens new opportunities for creating compact and functional optical and optofluidic microsystems for sensing, telecom and lab-on-a fiber applications.

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