Faraday rotation in femtosecond laser micromachined waveguides

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Abstract: We demonstrate magneto-optic switching in femtosecond-laser micromachined waveguides written inside bulk terbium-doped Faraday glass. By measuring the polarization phase shift of the light as a function of the applied magnetic field, we find that there is a slight reduction in the effective Verdet constant of the waveguide compared to that of bulk Faraday glass. Electron Paramagnetic Resonance (EPR) measurements confirm that the micromachining leaves the concentration of the terbium ions that are responsible for the Faraday effect virtually unchanged.

OCIS codes: (320.7090) Ultrafast lasers; (230.7370) Waveguides; (230.2240) Faraday effect; (350.3390) Laser processing of materials.

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1. Introduction

Femtosecond laser micromachining of transparent materials has many potential applications in integrated optics [1-11]. Many devices such as waveguides [1-5], splitters [10], Mach-Zehnder interferometers [8], resonators [7] and amplifiers [6, 9, 11] have been fabricated using this technique. In this paper, we combine oscillator-only micromachining and an externally switchable substrate to fabricate integrated active waveguides. Oscillator-only micromachining of waveguides does not require an amplifier and the pairing of this technique with a material whose properties can be externally controlled enable the fabrication of waveguides that can serve as active optical logic devices for integrated circuits.

One externally controllable material property that can be exploited to make switchable active devices is the magneto-optic effect, also known as Faraday effect [12]. The Faraday effect is a rotation of the light-polarization induced by a magnetic field applied to the material. The linear constant of proportionality between the angle of rotation and the applied magnetic field is called the Verdet constant, and is given by $V = \theta / BL$, where θ is the relative angle of polarization rotation, B is the magnitude of the applied magnetic field parallel to the direction of light propagation, and L is the material length over which the magneto-optic interaction takes place. The higher the Verdet constant, the larger the polarization rotation in response to an applied magnetic field, and the more suitable the material is for optical switching. Faraday rotation is widely used in optical isolators, preventing feedback in optical circuits.

Previously fabricated Faraday rotating waveguides for integrated optics include rib waveguides etched from Garnet films deposited on semiconductors [13-15] and waveguides produced by laser annealing [13]. All these waveguide fabrication methods require the deposition of a film of magneto-optic material onto a suitable substrate, which is costly and time consuming. In contrast, the waveguides we present in this paper can be easily written into bulk transparent material using oscillator-only femtosecond-laser micromachining, and the magneto-optic material is bulk Faraday glass, for which no deposition or growth is necessary. Furthermore, previous work in our group has shown that we can micromachine waveguides across multiple pieces of glass while maintaining good optical coupling between them [16], enabling the fabrication of an integrated Faraday isolator using femtosecond micromachining.

We demonstrate that oscillator-only femtosecond-laser micromachining can be used to fabricate waveguides inside terbium-doped Faraday glass. The resultant waveguides are magneto-optically active, and can be used for photonic applications. The measured effective Verdet constant of the waveguide is $3600° \pm 500°\ T^{-1}m^{-1}$ (0.22 ± 0.03 min/Oe·cm), comparable to that of the original material, which is $4300° \pm 200°\ T^{-1}m^{-1}$ (0.26 ± 0.01 min/Oe·cm). We further investigated the compositional modification induced by femtosecond-laser micromachining by Electron Paramagnetic Resonance (EPR) spectra of the Faraday glass before and after irradiation. We observe a slight increase in the concentration of Tb^{+4} ions, which is not significant enough to affect the waveguide's Faraday behavior.

2. Experimental

In Faraday glass, one class of magneto-optically active materials, rare-earth ions are responsible for the material's magnetic susceptibility. The commercial Faraday glass used in

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this experiment was purchased from Shanghai Institute of Optics and Fine Mechanics. The glass, known as TG20, is doped with Tb^{3+} ions and has a composition of Tb_2O_3-SiO_2-Al_2O_3-B_2O_3, with a homogenous Tb^{3+} ion concentration of 7.9×10^{18} ions/mm^3.

The Faraday glass is micromachined using 60-fs, 800-nm, 10-nJ laser pulses from an extended cavity oscillator at a 25-MHz repetition rate. The pulses are focused through a 1.4-NA microscope objective (with a nearly spherical spot size of about 1 µm in diameter) into the bulk of a 50 mm × 5 mm × 1 mm Faraday glass sample that is translated at a speed of 10 mm/s with respect to the laser beam. The waveguides are each written in one pass along the entire 50-mm length of the sample, and are spaced by 200 µm to prevent crosstalk between waveguides, as seen in Fig. 1. The top left inset of Fig. 1 shows a cross-sectional view of the micromachined waveguides, which have an average diameter of 8 µm. After micromachining the ends of the sample are polished to allow light to be coupled into the waveguides. We found multimode behavior at 632 nm, as shown in the top right inset of Fig. 1, and single mode behavior at 1550 nm.

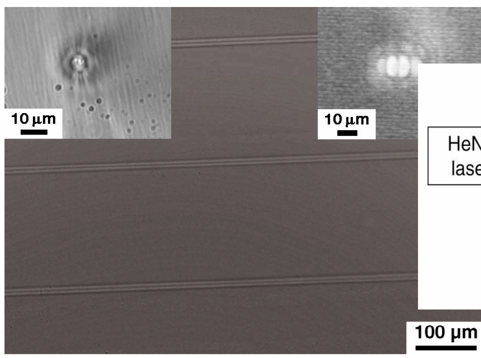

Fig. 1. Optical microscope image of micromachined waveguides inside the Faraday glass. Left Inset: Cross-sectional view of waveguide. Right Inset: Observed multimode behavior at 632 nm.

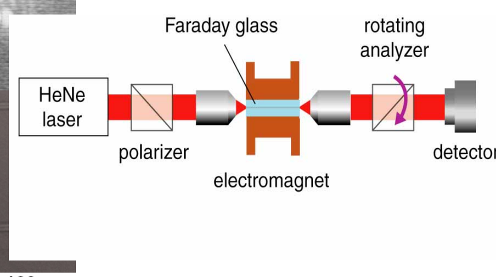

Fig. 2. Experimental setup for measuring Faraday rotation. A 632.8-nm laser beam is sent through a linear polarizer, coupled into and out of the sample using 10× microscope objectives, and finally analyzed by a rotating linear polarizer mounted on a motorized wheel.

We determined the magneto-optic response of the waveguides using the polarization rotation setup shown in Fig. 2. The micromachined Faraday sample is placed in a electromagnetic coil, which is mounted on a three-axis stage to facilitate alignment. HeNe laser light at 632.8 nm is coupled into and out of the waveguide using two 10× microscope objectives and an iris blocks any scattered light at the exit of the second objective lens. To determine the polarization rotation we use a rotating analyzer in front of the detector and a lock-in amplifier. The resulting signal is a sinusoidal function of the analyzer angle and any induced Faraday rotation inside the waveguide results in a phase shift of the detected sinusoidal signal.

As the field is not uniform across the length of the sample, the standard expression for the Faraday rotation has to be modified to account for the varying magnetic field profile, $B(x)$, along the length of the sample. Because the Faraday effect is a linear response of the material to the applied magnetic field, we can write

$$V = \frac{\theta}{\int_0^L B(x)dx} . \qquad (1)$$

To determine the Verdet constant of the material, we plot the phase shift of the signal as a function of the integrated magnetic field profile; the slope of the data then gives the Verdet constant.

3. Results

Figure 1 shows a close up of the femtosecond laser micromachined waveguides spaced by 200 µm under transmission optical microscopy. The micromachined waveguides look similar to those fabricated in glass using this process [5, 8, 17].

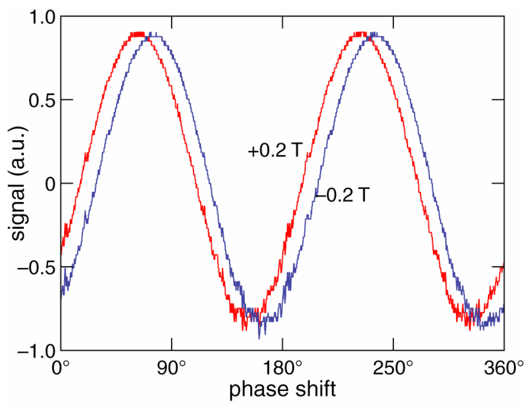

Fig. 3. Oscilloscope traces of the signal transmitted through the bulk Faraday glass for values of the integrated magnetic field profile of ±0.2 T·m. The observed phase shift gives the relative Faraday polarization rotation angle.

The dependence of the detector signal on the angle of the analyzer is shown in Fig. 3 for values of the integrated magnetic field profile of ±0.2 T·m. The phase shift between the two traces confirms that a Faraday rotation occurs inside the waveguide.

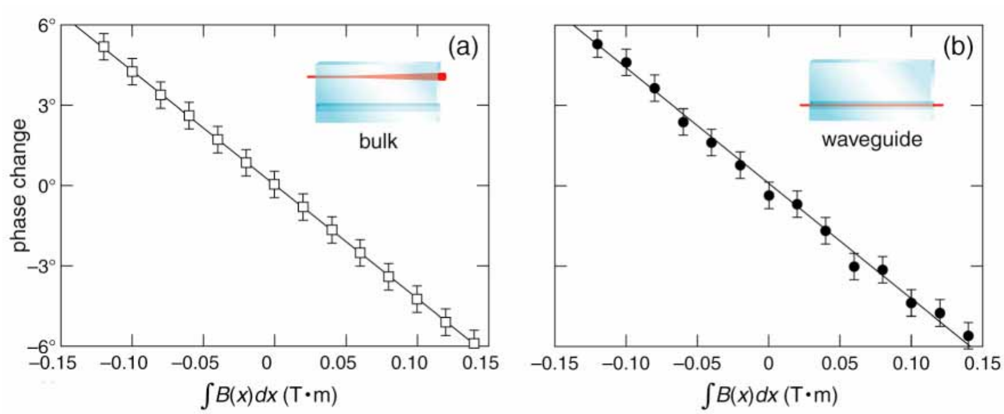

Fig. 4. Linear dependence of the induced phase change on the integrated magnetic field profile for (a) bulk Faraday glass and (b) a waveguide written in Faraday glass.

Figure 4(a) shows the dependence of the phase shift on the integrated magnetic field profile in bulk Faraday glass. In Fig. 4(b), we show the same data for the waveguide. The Verdet constant is the slope of a least-squares fit of the data to a straight line. Averaging several sets of data for both bulk glass and waveguides, we obtain an effective Verdet constant of 3600° ± 500° $T^{-1}m^{-1}$ for the waveguides, which is a slight reduction in the Verdet

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constant compared to that of the bulk Faraday glass (4300° ± 200° $T^{-1}m^{-1}$) to within the experimental error.

4. Discussion

Previous research [18, 19] has shown that UV irradiation can oxidize Tb^{3+} ions in Faraday glass into paramagnetic Tb^{4+} ions. Because our femtosecond micromachining technique relies on multiphoton absorption in the focal volume and because simultaneous absorption of three photons provides the same energy as a UV photon, it is possible that during micromachining Tb^{3+} ions are ionized into Tb^{4+} ions.

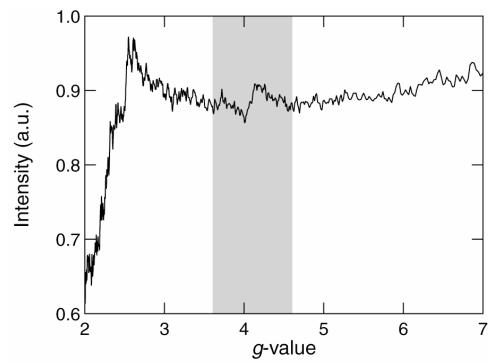

Fig. 5. Electron Paramagnetic Resonance spectrum of bulk Faraday glass. The shaded region shows the paramagnetic resonance due to the Tb^{4+} ions.

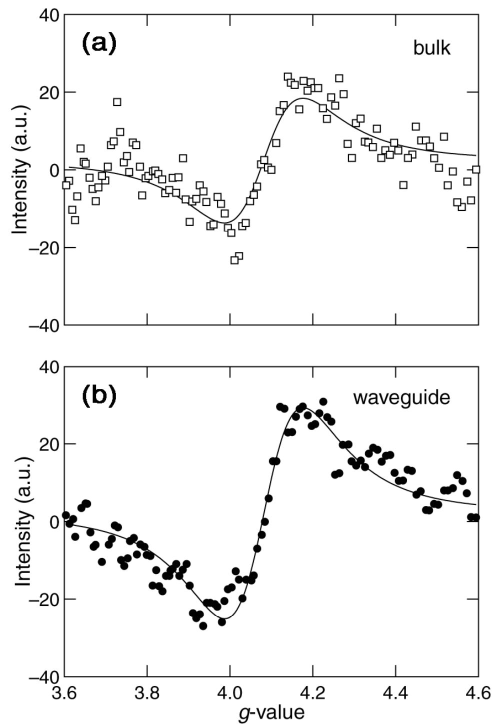

Fig. 6. Paramagnetic resonance due to the Tb^{4+} ions in the Electron Paramagnetic Resonance spectrum of Faraday glass (a) before and (b) after irradiation with femtosecond laser pulses. The curves show a Lorentzian fit to the data.

Because the terbium ions are responsible for the Faraday effect [20], we examined how femtosecond micromachining affects the concentration of Tb^{4+} ions using EPR spectroscopy. Figure 5 shows the EPR spectrum of the bulk Faraday glass. The highlighted region shows the resonant signature of the paramagnetic Tb^{4+} ions at a gyromagnetic ratio value of $g = 4.1$; this region is shown in greater detail in Fig. 6(a). The amplitude of the resonance is a measure of the ion concentration. For comparison, an additional sample was prepared by micromachining waveguides spaced 25 µm apart across the length of a piece of Faraday glass, irradiating approximately 2% of the sample's volume before grinding it up and obtaining an EPR spectrum [Fig. 6(b)]. Fitting both spectra in Fig. 6 with a Lorentzian curve, we find a 60% increase in the Tb^{4+} spectral intensity after laser micromachining, indicating that Tb^{4+} ions are generated during the waveguide writing process. Using a theoretical model and accounting for

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the percentage irradiated, [20] we estimate that there are a total of 5.5×10^{19} cm^{-3} Tb^{4+} ions after femtosecond-laser irradiation [20]. This resulting Tb^{4+} ion concentration is still negligible compared to the initial Tb^{3+} ion concentration of 7.9×10^{21} cm^{-3}, confirming that the micromachining process does not affect the ions responsible for the Faraday effect.

5. Conclusion

In summary, we demonstrate that it is possible to fabricate waveguides in Faraday materials using femtosecond micromachining. The fabricated waveguides exhibit no significant reduction in Verdet constant and the micromachined waveguides can be used as magneto-optic switches. We confirmed that the femtosecond-laser micromachining does not convert a significant fraction of the active Tb^{3+} ions into Tb^{4+} ions. These findings pave the way for light-by-light magneto-optic switching and integrated optical isolators.

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