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Trimming phase and birefringence errors in planar lightwave circuits with a deep ultraviolet femtosecond laser

Qiyang Chen, Kevin P. Chen, Michael Buric, and Suwas Nikumb

A deep ultraviolet femtosecond laser was employed to trim phase and birefringence errors in silica planar lightwave circuits. A permanent refractive index change of $\sim 3.8 \times 10^{-4}$ and a birefringence change of 1.0×10^{-4} were induced in hydrogen-free Mach-Zehnder planar waveguide circuits. The ultrafast laser enhances the ultraviolet photosensitivity response in silica waveguides by two orders of magnitude greater as compared to that observed by using a nanosecond 248-nm KrF excimer laser.

Introduction: Recently, femtosecond lasers have been shown to be effective tools for inducing refractive index changes in transparent dielectric materials [1-4]. Unlike the photosensitivity induced by nanosecond or CW deep UV laser radiation, ultra-high intensity femtosecond laser pulses drive multi-photon processes in glass to produce highly localized volume index changes well below the glass surface [1, 2]. This permits the fabrication of photonic structures including binary data storage [1], optical waveguide devices [2-3], and fiber gratings [4-5] in a wide variety of glass materials. Ultrafast laser trimming has also been demonstrated in interleaver waveguide devices [2]. Previous reports predominantly indicated the use of fundamental output from Ti:sapphire lasers operating around 800 nm, wavelengths far greater than the absorption region of many high bandgap materials, such as fused silica. In addition, the nonlinear optical processes are weak. Work on refractive index change using ultrafast UV wavelengths is also scarce in the literature. In this paper, we present a comparative study of

laser trimming in hydrogen-free commercial silica-on-silicon planar lightwave circuits using both a deep UV femtosecond laser and an UV nanosecond pulsed excimer laser.

Silica-on-silicon planar lightwave circuits (PLCs) realize the miniaturization of optical devices through integration into highly functional and compact packages. Current tolerances in semiconductor micro-fabrication of low-loss interferometric and arrayed-waveguide grating (AWG) components are not sufficient to control the phase errors as well as the TE and TM mode birefringence. We demonstrate herein that the process of trimming hydrogen-free PLCs with 258-nm femtosecond laser can achieve significant refractive index change and therefore realize complete compensation of the intrinsic birefringence of the PLCs. The enhancement of the ultraviolet photosensitivity response in germano-silica waveguides by femtosecond laser pulses is over two orders of magnitude greater than that achieved using a nanosecond 248-nm KrF excimer laser.

The waveguide samples used in this study were Mach-Zehnder (MZ)-type, frequency-domain modulators (FDM) on a silicon substrate. First, a $6 \times 6 \mu\text{m}$ germanium-boron-phosphor co-doped core was embedded in 40- μm -thick cladding glass to provide a $\sim 0.8\%$ refractive index contrast. Next, glass layers were deposited by flame hydrolysis for the formation of an interferometer structure. A 4-mm path difference in the two arms of the interferometer was created to yield a 0.4-nm (50 GHz) free spectrum range (FSR) centered on the 1550-nm telecommunication band. The fringe contrast was found to be ~ 14 dB. The waveguide facets were polished and pigtailed with polarization-maintaining (PM) fibers before laser trimming. After these initial preparations, a 5 mm-long section of the shorter arm of the PLC interferometer was irradiated with femtosecond laser pulses. The ultrafast laser system

consisted of a diode-pumped fiber oscillator, frequency-doubled Nd:YAG pump laser, and a Ti:sapphire regenerative amplifier (CPA-2010, Clark-MXR, Inc.) with a third harmonic generation system (STORC). The resultant output pulses had a maximum energy of 0.1 mJ at 258 nm and a pulse width of 150 fs. The pulse repetition rate was maintained at 1 kHz. A microscope objective was used to focus the Gaussian beam to 80- μm diameter spot. Samples were mounted on XY translation stages having a 0.1- μm step resolution for scanning along the waveguide arm. The on-target peak power was estimated to be $\sim 113 \text{ GW/cm}^2$, which was well below the damage threshold of the glass material. The changes within the waveguide samples were examined using interferometric measurements by WYKO interferometer (model NT-2000) after trimming. Refractive index changes and the device characteristics were inferred in-situ from transmission spectra using an optical spectrum analyzer (Ando AQ6317B) and an Erbium broadband light source (EBD-7210, MPB Communications, Inc.).

Results and discussion: Monitoring the transmission spectra of both TE- and TM-modes from an FDM sample before and after laser trimming showed the spectral shift ($\Delta\lambda$) towards shorter wavelengths governed by an increase in the effective refractive index (Δn). Evaluation using the equation $\Delta n = \Delta\lambda \cdot \lambda / (\Delta\lambda_{\text{FSR}} \cdot L)$ (see Ref. [6]) yields a Δn value of about 3.8×10^{-4} , corresponding to the observed spectral shift ($\Delta\lambda$) of 0.49 nm for TE modes at an accumulated fluence of 23.6 kJ/cm^2 . Values used in this calculation were probe wavelength $\lambda = 1563 \text{ nm}$, free spectral range $\Delta\lambda_{\text{FSR}} = 0.4 \text{ nm}$, and trimmed arm length $L = 5 \text{ mm}$. The result indicates a shift in the spectrum more than 1.2 times that of the $\Delta\lambda_{\text{FSR}}$.

The effective refractive index changes (Δn) are shown in Fig. 1a for the various FDMs as a function of accumulated laser fluence. It should be noted that the Δn values were unsaturated

for all the samples. In addition, there was no noticeable degradation of the fringe visibility, indicating no additional insertion losses were induced due to laser trimming. For comparison, trimming of similar hydrogen-free FDM samples with pulses from a 10-ns, 248-nm, KrF laser (Lumonics PF240) used an accumulated fluence of 40-kJ/cm^2 (200 mJ/cm^2 single pulse fluence), which yielded only a $\sim 2 \times 10^{-5}$ index change for the TE mode and a $\sim 2 \times 10^{-4}$ index change after $\sim 300\text{ kJ/cm}^2$ fluence. This comparison highlights the effectiveness of the ultrafast laser induced refractive index changes. Compared to trimming with KrF laser, a photosensitivity enhancement of more than 40-times can be attributed to the short-pulse effects from the femtosecond lasers.

Figure 1a also shows that the TE mode index change (Δn_{TE}) increases more quickly as compared to the TM mode index (Δn_{TM}). The waveguide birefringence ($\Delta n_{\text{TE}} - \Delta n_{\text{TM}}$) is plotted as a function of the effective refractive index change of the TM mode in Fig. 1b. This illustrates the effectiveness of the technique to trim birefringence, while also indicates its inability to independently change Δn . The birefringence constitutes $\sim 30\%$ of the mean index change with an achievable birefringence value of $\sim 1.0 \times 10^{-4}$. This birefringence response is much larger than that associated with the nanosecond laser pulses. For example, 2-3% relative birefringence is achieved with low-fluence at 193-nm ArF laser irradiation and 20% relative birefringence resulted from larger fluence at 193-nm waveguide trimming [6].

The native waveguide birefringence in currently manufactured FDMs greatly impairs device performance as manifested in Fig. 2a for hydrogen-free samples at room temperature. Independently, the TE- and the TM-modes generate a 14-dB FDM spectrum. Both modes produce only a 3.5-dB modulation depth when presented equally together prior to the laser

trimming. The 0.14-nm fringe shift between TE and TM modes corresponds to a 1.1×10^{-4} index birefringence over the 5 mm path difference in the interferometer arms. Figure 2b shows that femtosecond laser birefringence trimming can completely compensate the intrinsic waveguide birefringence. The full 14-dB modulation was recovered for the combined TE and TM mode propagation by irradiating the 5 mm length of the interferometer arm with an average fluence of 16.5 kJ/cm^2 .

The UV femtosecond laser trimming introduced herein offers significantly better absolute phase and birefringence changes than those realized using nanosecond lasers. Laser-induced modified structures (optical damages) have been suggested as the mechanism causing refractive index changes induced by infrared (800 nm) ultrafast laser radiation [2,4,7,8]. Therein, significantly large peak intensities from 10^{12} W/cm^2 to 10^{18} W/cm^2 were used to alter the refractive index [2-4]. Although index changes with a magnitude up to 10^{-2} were reported, the optical damages also induced large optical losses, which limit the application of photonic devices fabricated entirely using ultrafast lasers. It should be noted that the peak power intensities applied in our experiment were substantially smaller at $\sim 113 \text{ GW/cm}^2$. No noticeable increase in the optical loss was found at these intensities, suggesting two-photon absorption may be responsible for the index change. The results presented in this letter are also consistent with previous work on the inscription of gratings by UV femtosecond laser radiation [5].

Conclusion: We demonstrate that a deep ultraviolet femtosecond laser is a valuable tool for trimming phase and birefringence errors in silica planar lightwave circuits. Trimming with femtosecond laser pulses at 258 nm wavelength achieved refractive index changes as large as

3.8×10^{-4} in hydrogen-free PLCs using very low laser fluences. This results in tuning the wavelength response of PLCs as well as provides significant birefringence trimming ($\sim 1.0 \times 10^{-4}$) for complete compensation of the intrinsic birefringence in PLCs. The results demonstrate a new method for ultrafast laser photosensitizing glass photonic component fabrication with the potential to simplify existing fabrication processes and to improve device performance.

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Figure captions:

Fig. 1 *Effective refractive index change as a function of the 258-nm femtosecond laser irradiation dosage for TE and TM modes and laser-induced birefringence of FDMs*

a) Effective refractive index change

b) Laser-induced birefringence

Fig. 2 *Transmission spectra of an FDM for TE, TM, and equal TE/TM (45°) input polarization*

a) Initial performance

b) Performance after the 258-nm femtosecond laser trimming where waveguide birefringence has been completely compensated

Figure 1. (Q. Chen *et al.*, Trimming phase and birefringence errors in planar lightwave circuits ...)

Figure 2. (Q. Chen *et al.*, Trimming phase and birefringence errors in planar lightwave circuits ...)