Waveguide electro-optic modulator in fused silica fabricated by femtosecond laser direct writing and thermal poling

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Received August 30, 2005; revised November 14, 2005; accepted December 1, 2005; posted December 5, 2005 (Doc. ID 64516)

An integrated electro-optic waveguide modulator is demonstrated in bulk fused silica. A Mach–Zehnder interferometer waveguide structure is fabricated by direct writing with a femtosecond laser followed by thermal poling. A 20° electro-optic phase shift is achieved at an operating wavelength of 1.55 μm with an applied voltage of 400 V and an interaction length of 25.6 mm, which correspond to an estimated effective electro-optic coefficient of 0.17 pm/V for the TE-polarized mode. © 2006 Optical Society of America

OCIS codes: 130.3120, 190.4390, 230.2090, 320.7160.

Fused silica has a number of excellent properties that include fiber compatibility, excellent transparency from the UV to the near IR, and low cost, making it a desirable substrate material for integrated optics applications. The application of thermal poling to produce second-order nonlinearity in glass has extended the uses of glass integrated devices into the nonlinear regime.[1] Second-order susceptibility $\chi^{(2)}$, introduced by thermal poling, allows the linear electro-optic (EO) effect to be utilized in poled glass. Poling phenomena have been studied in bulk glass, fiber, and thin-film planar glass waveguides. The first demonstration of EO phase modulation in a fused-silica channel waveguide was reported by Liu *et al.*[2] The electron-beam-written waveguide was thermally poled and measured in a free-space Mach–Zehnder interferometer (MZI). A phase shift of 32 mrad at a wavelength of 633 nm was achieved with an applied voltage of 1100 V and an interaction length of 4.8 mm, corresponding to an effective EO coefficient (the polarization state, TE or TM, was not specified) of 0.06 pm/V. The measurement of EO coefficients in thermally poled bulk fused silica was performed in a free-space MZI by Long *et al.*,[3] who found the effective EO coefficients, r_{31} and r_{33}, to be 0.1 and 0.3 pm/V, respectively. Abe *et al.* demonstrated the first integrated EO switch fabricated in a thermally poled thin-film glass waveguide.[4] The 36 cm long MZI device was produced by reactive ion etching channel waveguides in GeO_2 thin film. A switching voltage of 1.7 kV was demonstrated, and the effective EO coefficient for the TM mode, r_{33}, was found to be 0.02 pm/V. Ren *et al.* thermally poled a Ge:SiON channel waveguide fabricated by plasma-enhanced chemical vapor deposition and UV writing.[5] The effective EO coefficients for both TM mode and TE modes, r_{33} and r_{13}, were determined to be 0.076 and 0.07 pm/V, respectively, by use of a fiber-based MZI. Similar results with a thermally poled integrated GeO_2-doped silica ridge waveguide MZI,[6] in which the EO coefficients for both the TM mode and the TE mode were found to be 0.05 pm/V, were also reported by Cao *et al.*

The highest value of $\chi^{(2)}$ induced by thermal poling in glass has been demonstrated in bulk fused silica rather than in deposited thin-film glass. The demonstration of an integrated EO waveguide device in thermally poled bulk fused silica has yet to be reported, however, because waveguide fabrication techniques for this material have until recently been limited. In the past few years it has been demonstrated that femtosecond laser direct writing technology can be used to fabricate low-loss waveguides (<0.1 dB/cm) and complex waveguide devices in glass.[7–9] In this Letter we report the use of a femtosecond laser direct-writing technique, together with thermal poling, to demonstrate an EO modulator based on a three-dimensional integrated MZI waveguide structure fabricated in bulk fused silica.

We used a 1.6 mm thick Herasil fused-silica substrate in this study. The glass was diced into a 45 mm × 25 mm chip, and both ends were polished. Aluminum alignment marks were lithographically patterned on the surface of the sample to serve as reference markers for direct writing and electrode placement. The MZI structure, as illustrated in Fig. 1, was fabricated by focusing (microscope objective N.A., 0.55) a femtosecond laser ($\lambda = 790$ nm; pulse width, 110 fs; repetition rate, 238 kHz; pulse energy, 200 nJ) slightly below the top surface of the sample while the sample was moved (scan speed, 100 μm/s), using a computer-controlled translation stage. The input Y splitter and the output directional coupler were written 48 μm below the surface, while the arms of the MZI were written 11 μm below the surface (measured from the center of waveguides). The depths of the written waveguides were verified by measuring the refractive-index profile of the waveguides, using a refracted near-field (RNF) profilometer. The refractive-index profile of one of the MZI arms is

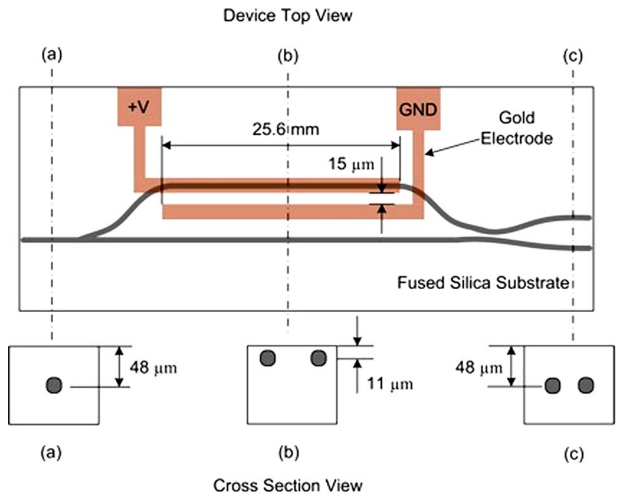

Fig. 1. (Color online) Schematic diagram of a three-dimensional integrated MZI-type EO modulator.

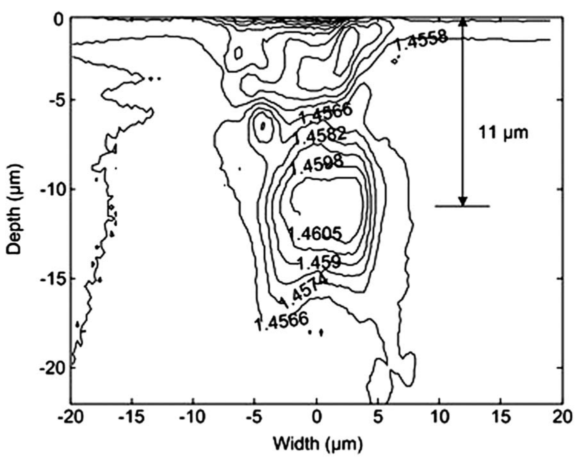

Fig. 2. Refractive-index contour plot of the femtosecond laser direct-written waveguide measured by a RNF profilometer.

shown in Fig. 2. The MZI arms were written close to the surface to maximize the spatial overlap between the waveguide mode and the thin nonlinear layer induced by thermal poling. The remaining MZI components were buried somewhat deeper to avoid surface and edge defects and also to demonstrate the three-dimensional capability of the direct-writing technology.

The MZI sample was then sandwiched between two electrodes of an n-type silicon wafer and thermally poled in a box furnace at 275°C for 10 min with an applied voltage of 4 kV. The poling voltage was increased to 5 kV when the sample was allowed to cool inside the furnace.[10] It took ~20 min for the sample's temperature to reach 210°C, the temperature at which poling stops.[1] The applied voltage was removed when the sample reached room temperature. Although the refractive-index profiles of the waveguides were not remeasured following poling, we do not believe that poling resulted in any significant changes.

A Maker fringe measurement, shown in Fig. 3, was made with a p-polarized fundamental beam from a Nd:YAG pulsed laser at 1064 nm (pulse duration, 0.62 ns; peak power, 16.9 kW; repetition rate, 6.5 kHz). The second-order nonlinear coefficient is a tensor thought to correspond to the $4mm$ symmetry class group with $d_{13}=d_{15}=d_{33}/3$,[11] where $d_{ij}=\chi_{ij}^{(2)}/2$. Thus the nonlinear coefficients are given by

$$\begin{bmatrix} 0 & 0 & 0 & 0 & d_{31} & 0 \\ 0 & 0 & 0 & d_{31} & 0 & 0 \\ d_{31} & d_{31} & d_{33} & 0 & 0 & 0 \end{bmatrix}.$$

No attempt was made to directly measure the spatial profile of the nonlinearity, but we simply assumed a step shape to obtain a crude estimate of the magnitude and the depth of the induced nonlinearity. We note that recent direct measurements indicate that the profile is not steplike.[12] Using an X-cut quartz crystal as a reference ($d_{11}=0.5$ pm/V) together with these assumptions, we computed $\chi_{33}^{(2)}$ and the depth of the nonlinear region to be 0.25 pm/V and 20 μm, respectively, from the Maker fringe measurement.

Gold electrodes with an interaction length of 25.6 mm and a spacing of 15 μm were patterned along one arm of the MZI (Fig. 1) by sputter coating and a lift-off process. A broadband amplified spontaneous emission source operating in the vicinity of 1.55 μm was passed through a polarizer, and the TE mode was coupled into the input end of the Y splitter by a 20× objective lens. The beams from the modulation arm and the reference arm were combined at the directional coupler, and the output signal was collected and directed into an optical spectrum analyzer. The device was tested by applying various dc voltages to the electrodes while we collected the spectra of the MZI output. The results are shown in Fig. 4. Only the TE mode was studied because this polarization, as opposed to TM polarization, experienced negligible absorption loss due to the presence of the gold electrode placed directly on top of the waveguide. The extinction ratio of the device was only ~5.5 dB because the Y splitter and the directional coupler were not optimized.

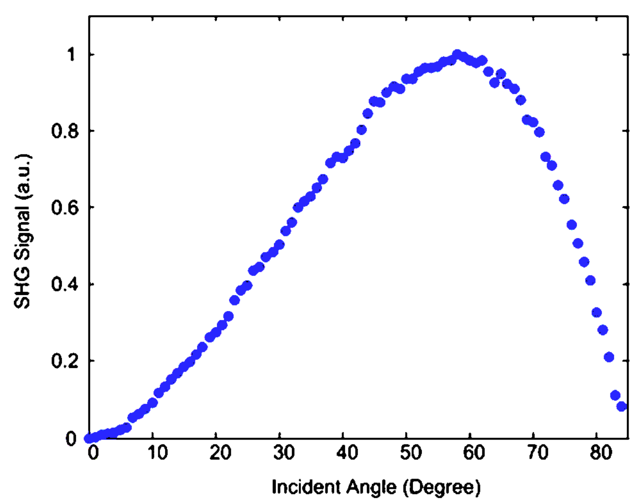

Fig. 3. (Color online) Maker fringe measurement data on the thermally poled MZI sample for p polarization. SHG, second-harmonic generation.

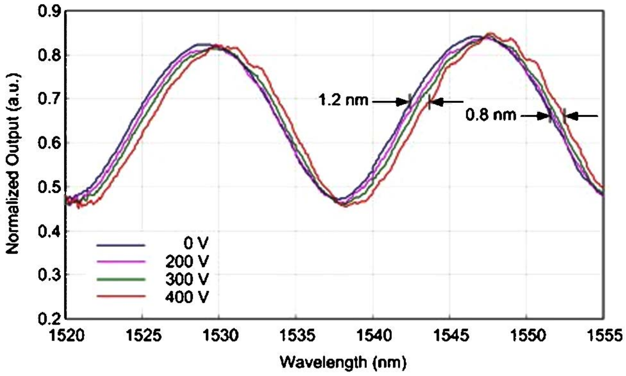

Fig. 4. (Color online) Spectral responses of the integrated MZI-type EO modulator at four voltages.

As shown in Fig. 4, an average spectral shift of 1 nm in the output spectrum was achieved with an applied voltage of 400 V. The EO phase shift, $\Delta\phi$, under the electrode is given by

$$\Delta\phi = \frac{2\pi r_{13}^{eff} n^3}{\lambda \quad 2} EL, \tag{1}$$

where n is the refractive index of the glass (approximately 1.45), r_{13}^{eff} is the effective EO coefficient for the TE mode, E is the applied electrical field (measured normal to the glass surface), L is the electrode length, and λ is the operating wavelength. The value of the effective EO coefficient includes a term that accounts for the spatial overlap between the waveguide mode and the induced nonlinear profile.

A computation of the electric field distribution under the electrode showed that the field strength, E, is ~ 2 times smaller than V/g, where V is the applied voltage and g is the gap between the electrodes. Using the data of Fig. 4 and Eq. (1), we found r_{13}^{eff} to be 0.17 pm/V. We believe that this is the largest value reported to date for a thermally poled waveguide device. Furthermore, by using the TM- rather than the TE-polarized mode, we anticipate a factor-of-3 increase in the effective EO coefficient in bulk fused silica,[3] although a similar effect has not been seen in deposited thin films.[5,6]

The EO coefficients are approximately given by

$$r_{ij} \approx 2\frac{\chi_{ij}^{(2)}}{n^4}. \tag{2}$$

Thus, if we were to *assume* that the induced nonlinearity had a step profile, our $\chi_{33}^{(2)}$ of 0.25 pm/V would correspond to an $r_{13}=r_{33}/3$ of 0.04 pm/V.

In conclusion, we have demonstrated what is to the best of our knowledge the first integrated EO waveguide modulator in bulk fused silica by taking advantage of both femtosecond laser direct writing and glass thermal poling technologies. We have also achieved the largest effective EO coefficient reported to date for a thermally poled integrated optic waveguide device. A 1 nm spectral shift in the vicinity of 1.55 μm was obtained in a MZI-type EO waveguide modulator with an applied voltage of 400 V, corresponding to an estimated effective EO coefficient, r_{13}^{eff}, of 0.17 pm/V. Based on our results, we expect that by optimizing the depth of the waveguide and using the TM-polarized mode we can achieve a V_π switching voltage of below 1000 V by using 25 mm long electrodes. Although the performance of the integrated EO modulator reported here does not compare favorably with that of modulators based on conventional EO materials, such as lithium niobate, the proposed technique is scientifically interesting in its own right. Furthermore, other glasses may eventually be found that yield much higher EO coefficients on poling and (or) have high transmission in spectral regions where conventional devices do not. A thorough scientific investigation of the thermal poling of glass regions that have previously been modified by femtosecond laser writing also remains to be done.[13]

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