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Thermally Poled Channel Waveguides With Polarization-Independent Electrooptic Effect

Yitao Ren, Carl Johan Marckmann, Jesper Arentoft, and Martin Kristensen

Abstract—In this letter, we present a systematic investigation of the poling-induced electrooptic (EO) effect in germanium and nitrogen codoped channel waveguides. The channel waveguides show attractive properties: 1) almost polarization independent EO effect; 2) a flat frequency response with the modulation frequency up to 100 kHz; and 3) low linear loss and low polarization dependent loss, which demonstrate great technological potential.

Index Terms—Channel waveguides, electrooptic devices, glass, integrated optics, nonlinear optics, waveguides.

SUBSTANTIAL nonlinearity in silica glass was discovered a decade ago [1] as a result of breaking its centro-symmetric structure by a thermal poling process, which offers great prospect to make new classes of electrooptic (EO) glass devices. Since then, efforts [2]–[6] have been devoted to achieve a further increase of the nonlinearity in glass material, to clarify the mechanism behind the nonlinearity and to explore new glass systems. Comparatively, the thermal poling technique creates a more stable nonlinearity in glass among the available methods [2], [7]–[9] inducing the nonlinear effect. Less research work has been spent on the poling of glass waveguides [10]–[13] compared to studies on the poling of bulk silica [1], [3], [14], [15] and silica fibers [6], [16]–[18]. Silica-based waveguides with high nonlinearity will challenge the position of the expensive crystals such as LiNbO_3 and provide practical applications in producing integrated electrooptic (EO) modulators, switches, wavelength converters, and electric field sensors because of silica's low manufacture cost, thermal stability, good optical properties, and excellent integrability with available silica-based devices and good interfacing to optical fibers.

Here, we present new results on the EO effect induced in germanium and nitrogen codoped channel waveguides that exhibit a weakly polarization dependent EO effect and low linear loss. The improved EO coefficient reaches $r = 0.076 \text{ pm/V}$ at a poling field of $208 \text{ V}/\mu\text{m}$.

Waveguide samples with three-layer structure were fabricated on n-type silicon wafers. The lower and upper cladding layers of pure SiO_2 were grown by thermal oxidation and plasma enhanced chemical vapor deposition (PECVD), respectively. The guiding layer by PECVD consisted of germanium-doped silicon oxy-nitride, Ge:SiON ($\sim 20 \text{ mole } \% \text{ Ge}$ and $\sim 10 \text{ mole } \% \text{ N}$).

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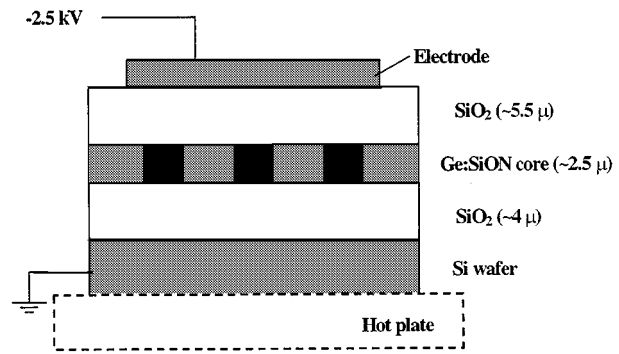


Fig. 1. The sample structure and a schematic drawing of the poling process.

Waveguide channels ($\sim 6\text{--}7 \mu\text{m}$ in width) with $250\text{-}\mu\text{m}$ separation were then written in the guiding layer by UV radiation (KrF excimer laser, 248 nm) through an aluminum mask after a high-pressure deuterium loading. The cleaved samples ($\sim 2 \times 2.5 \text{ cm}^2$) were poled with a static electric field (negative bias) at elevated temperature ($>330 \text{ }^\circ\text{C}$) in air on an open hotplate while the silicon wafer was kept grounded. The high dc voltage, -2.5 kV with respect to the ground, was applied across the samples via electrodes (a small rectangular silver paint area on the top of the samples and the silicon wafer) for poling. The poling time is counted from the voltage is turned on at the constant temperature required for waveguide poling until heating of the samples is stopped. The voltage was maintained during cooling off. The sample structure and schematic poling are shown in Fig. 1.

A fiber-based (single mode) Mach-Zehnder interferometer was utilized to measure the induced linear electrooptic (LEO) effect from the thermal poling. Laser light (1550 nm) coupled from an external cavity semiconductor laser was divided into two equal beams (measurement and reference arms) via a 3-dB coupler and the modulated signal from the sample in the measurement arm was then combined with the reference signal by another 3-dB coupler leading to a detector with frequency filter. A commercial LiNbO_3 phase modulator was employed in the reference arm to calibrate the phase shifts induced from the poled channel waveguide. Through a polarizer the desired polarization states into the samples was controlled to the direction parallel (p -component input) or perpendicular (s -component input) to that of the applied testing field. The interference fringes with highest contrast were achieved by balancing the intensity and matching the polarization states in both arms. A permanent EO effect was observed in all samples after poling. The induced LEO effect in the waveguides can be removed completely through depoling by heating the samples at $395 \text{ }^\circ\text{C}$ for

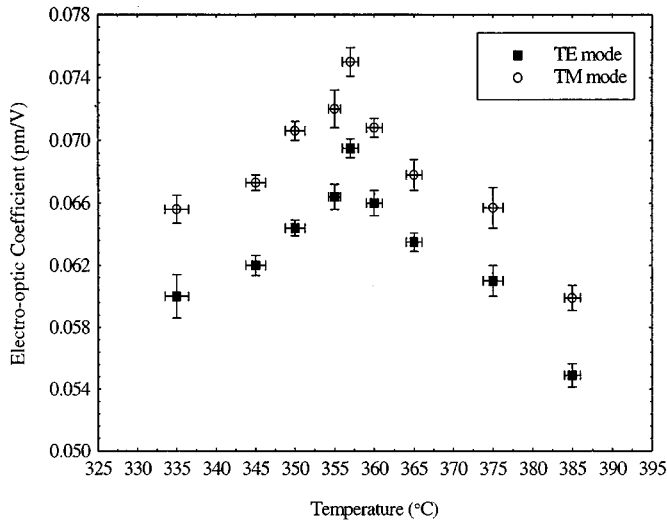


Fig. 2. EO coefficients as a function of the poling temperature for the sample poled at -2.5 kV for 30 min.

an hour and cooling them down. No noticeable degradation of the LEO signal was observed for our samples after 18 months storing at ambient conditions without special care.

During the characterizations of the samples a sinusoidal signal with frequency 5–100 kHz and amplitude ~ 100 V_{pp} (peak-to-peak) was applied. The induced phase shift $\Delta\varphi = 2\sin^{-1}(\Delta V/V_{\text{contr}})$ is obtained by comparison of the maximum signal (contrast V_{contr}) induced from the phase shift of the commercial modulator with that from the waveguide samples (modulated signal ΔV). V_{contr} and ΔV were measured at the same frequency to get rid of response drift with frequency from the experimental components. The linear EO coefficient (r) is then calculated by

$$r = \frac{\lambda t}{\pi V L n^3} \Delta\varphi$$

where λ is the wavelength, t is the thickness of the samples (the gap between the electrodes), V is the testing voltage, L is the length of the top electrode, and n is the refractive index of the guiding layer. The overlap factor is assumed to be one.

The influence of poling conditions (poling temperature and time) on the EO coefficient was studied. The corresponding results are shown in Figs. 2 and 3. Temperature studies (Fig. 2) clearly show that an optimum poling temperature ($T_{\text{opt}} = 357^\circ\text{C}$) exists to achieve a maximum EO signal for the waveguides at the given poling duration (30 min) and voltage (-2.5 kV). The poling temperatures were measured at the surface of the samples. The EO coefficients dropped once the poling temperature shifted away from T_{opt} . When the sample was poled at -2.5 kV and T_{opt} for variable time, the obtained results (Fig. 3) demonstrate that the nonlinear effect was built up quickly in the sample during the initial poling stage and saturated exponentially, which is qualitatively consistent with previous measurements in fused silica [4]. Small changes of the EO coefficients were observed when poling between 10 and 30 min. The EO coefficients decrease slightly when poling for a prolonged time. This may be due to a poor spatial

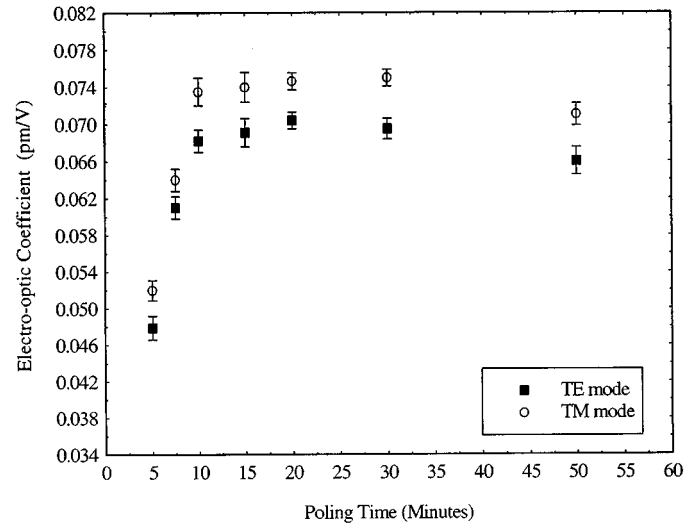


Fig. 3. EO coefficients versus the poling time for the sample poled at 357°C and -2.5 kV.

overlap between the depletion region and the waveguide mode in the guiding layer of the sample. No dc voltage higher than -2.5 kV was applied to the samples to avoid electrical breakdown during poling. The maximum EO coefficients ($r_{\text{TM}} = 0.076 \pm 0.001$ pm/V, $r_{\text{TE}} = 0.070 \pm 0.001$ pm/V) are achieved for a sample of $12\text{-}\mu\text{m}$ thickness thermally poled at optimum conditions (357°C , -2.5 kV for 30 min). The deduced $\chi^{(2)}$ is ~ 0.2 pm/V if $\chi^{(2)} = rn^4/2$ [2], which is correct in case of no dispersion of $\chi^{(2)}$ and perfect overlap between the waveguide mode and the nonlinear area. Poling of samples with a negative bias rather than a positive one reduces the risk of electrical breakdown and prevents the injection of cations (e.g., Ag^+) into the waveguides from the top electrode during poling. Cations in the waveguides may dramatically increase $\chi^{(2)}$, but also lead to higher propagation losses and large wavelength dependence for $\chi^{(2)}$ [19]. The frequency response of the EO signals was obtained from 5 to 100 kHz as shown in Fig. 4. The electrostrictive effect is not found at low frequency because of a basically flat response with frequency. Since higher frequencies could not be applied to the samples in the present setup, we made a simple test of the maximum switching speed by exciting the top electrode of another waveguide sample poled under similar conditions using an electrical pulse with a rise-time of a few nanoseconds. The optical phase response of the transmitted light and the electrical response of the top electrode were measured by a 100-MHz oscilloscope. The two curves were proportional each other within the experimental uncertainty of about 10% [20]. Therefore the electrostrictive effect is excluded up to 100 MHz.

The obtained results show the EO coefficients for the TM mode r_{TM} are slightly larger than those for the TE mode r_{TE} . However, they share similar dependence on the changes of temperature, time, and frequency. A ratio ($\gamma = r_{\text{TM}}/r_{\text{TE}} \approx 1.1 \pm 0.03$), corresponding to the ratio of r_{33}/r_{13} , was measured in experiments, which indicates a weakly polarization-dependent phase shift or EO effect. Though it is generally accepted that a frozen-in field built by thermal poling is responsible for the nonlinearity induced in poled silica, silica-based waveguides and

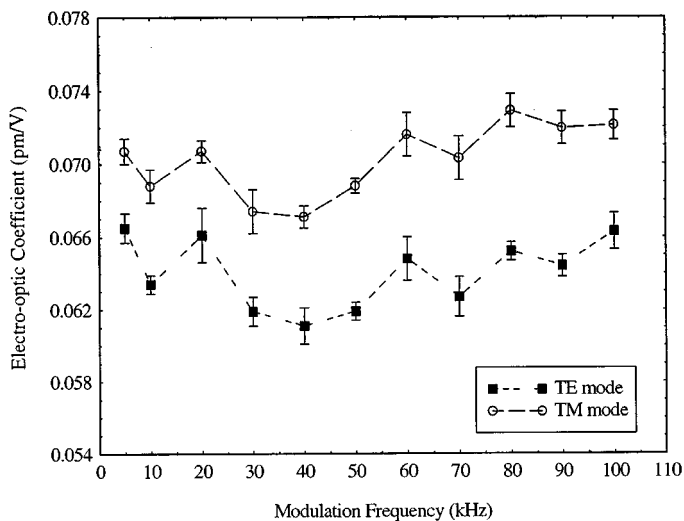


Fig. 4. The frequency response of EO coefficient for the sample poled at 357 °C and -2.5 kV for 30 min.

fibers, this γ value casts some doubt on the space charge electric-field mechanism since $\gamma = 3$ is predicted theoretically [21]. We believe that the significant deviation from the theory may either be related to dispersion of $\chi^{(3)}$ or to an unexpected tensional nature of $\chi^{(3)}$. The tensional effects may be partially related to stress in the glass. Polarization dependence and acoustic resonance are general concerns associated with electrooptic devices and have to be damped or removed. Accordingly, the weakly polarization dependent EO effect and flat frequency response (Fig. 3), no doubt, are technological advantages for the channel waveguides to produce active EO devices, such as polarization-independent phase modulators and switches. Moreover, the waveguides show low linear loss (<1 dB/cm) and weakly polarization-dependent loss (<0.2 dB/cm).

In conclusion, an improved EO channel waveguide, with weakly polarization-dependent EO effect, a flat frequency response and low linear loss, was demonstrated. The obtained EO coefficient is the largest reported in silica-based channel waveguides to the knowledge of the authors. Further work is in progress to optimize the waveguide structure and to bring the waveguide EO coefficient closer to the higher values obtained in poled bulk silica.

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