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Nonlinear effect induced in thermally poled glass waveguides

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Abstract: Thermally poled germanium-doped channel waveguides are presented. Multilayer waveguides containing a silicon oxynitride layer were used as charge trapper in this investigation on the effect of the internal field inside the waveguide. Compared to waveguides without the trapping layer, experimental results showed that the induced linear electro-optic (EO) coefficient increases about 20% after poling, suggesting strongly that the internal field is relatively enhanced, and showed it is a promising means for improving nonlinearity by poling in waveguides.

Key words: Electro-optic (EO) effect, Waveguides, Glass, Poling
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INTRODUCTION

Because of high transparency of glass to light and the very stable physical properties of glass, waveguides made of it are popular structures and building blocks in optoelectronic applications. Particularly they are often used to fabricate passive components or devices with good compatibility with optical fibers in optical communication. By adopting the technology available in microelectronics, fabrication of glass waveguides can be a standard process with mass production, which reduces the fabrication cost of glass waveguides tremendously and offers versatile functions suitable for various practical applications. However, silica glass is a kind of amorphous material with centrosymmetry structure, which prevents it from showing second-order nonlinear effect, and limits its applications in optical communication to build active structures. As the fast development and progress in optical communication and integrated optics, compact active components offering smart functions and easy integration are highly required. Polling of glass waveguides is then explored vigorously to seek new functions under the fast development.

The centrosymmetry structure of glass is destroyed by polling, and second-order nonlinear effect or linear electro-optic (EO) effect is built in glass (Myers *et al*., 1991), which opened a new horizon for the development and production of possible active optical waveguide elements with less cost and has triggered extensive researches due to the huge potential to develop low-cost, integrated nonlinear silica components on chips, such as EO modulators, switches and wavelength converters.

Polling of glass is carried out by applying an external field across the samples, with appropriate excitation sources (e.g., heat, light, etc.) being added during poling. UV light (Fujiwara *et al*., 1997) and electron beam radiation (Kazansky *et al*., 1993) are also introduced in the polling process instead of heating. Thermal poling technique creates a relatively more stable and reproducible nonlinearity in glass. In the thermal polling process (Myers *et al*., 1991), the samples are heated up to 250 °C~400 °C typically, with the temperature maintained for a period of time. The heating of the sample is then cut off while the voltage is preserved till room temperature is reached. Nonlinear optical property is eventually induced in glass materials by the polling process. The available experimental results favour the space-charge distribution (Kazansky and Russel, 1994) suggesting formation of a depletion region in glass materials. In addition, a contribution to the nonlinear effect from the reorientation of dipoles under the poling field cannot be ruled out completely in the poled materials. In poled bulk silica material, the moved charges are frozen in the glass during the cooling process and several micrometers thick depletion region is formed under the anode by the movement of charges. An effective optical nonlinearity ($\chi_{\text{eff}}^{(2)}$) is achieved in the depletion region through a built-in internal field ($\boldsymbol{E}_{\text{int}}$) interacting with the third-order nonlinearity ($\chi^{(3)}$) of the silica material, $\chi_{\text{eff}}^{(2)}=3\chi^{(3)}\boldsymbol{E}_{\text{int}}$.

Unfortunately, the poling-induced second-order nonlinear effects till now are either too small to be used in components or difficult to reproduce. A large and significant nonlinear effect in glass is of great importance to achieve a practical application. Because of existence of interfaces in waveguides, the nonlinear effect induced in the poled waveguides is normally small. Interface effect makes the poling of waveguides more complicated compared to the poling of bulk glass which can yield nonlinear coefficient of up to 1.6 pm/V in Ge-doped silica film (Ozcan *et al.*, 2004). It turned out that one of the keys to achieve higher nonlinear effect in glass waveguides is to increase the built-in electric field in the waveguides.

EXPERIMENTS AND RESULTS

Two groups of waveguide samples were fabricated by plasma enhanced chemical vapor deposition (PECVD) grown on silicon wafers. (1) The first group was composed of three-layer waveguides with pure SiO_2 buffer and top-cladding layer, and the core layer of the waveguide is germanium-doped silicon oxynitride containing ~5 at.% germanium and ~5 at.% nitrogen respectively; (2) The second group was composed of multilayer waveguides to which a silicon oxynitride layer (SiON, ~9 at.% N) was added based on the first group, where the added layer served as charge-trapping center to increase the density of the charge deposited on the top of the core layer as shown in Fig.1. Subsequently after a high-pressure deuterium loading, waveguide channels were formed in the core layer under ultraviolet (UV) radiation (KrF excimer laser, 248 nm) through an aluminum mask. The pulse fluence of the UV radiation for the waveguide structure depends on the core doping level of the waveguides; about 3% increase in the refractive index of the core was obtained to maintain single mode property in all formed channels from 4 to 10 μm in width. The waveguides show low linear loss (<1 dB/cm) and weakly polarization dependent loss (<0.2 dB/cm).

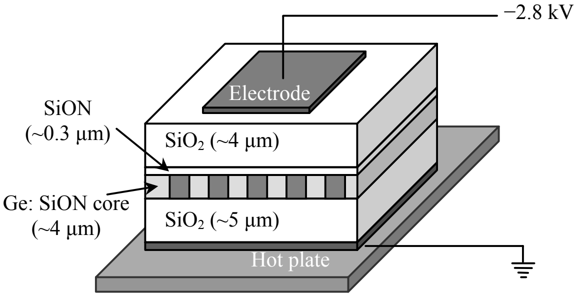

Fig.1 The schematic waveguide structure and the poling set-up

Silver paint electrode was put on the top of the cleaved waveguide chips. The chips were poled at a large static electric field (negative bias referred to the silicon wafers) at elevated temperature (>300 °C) in air on an open hotplate while the silicon wafer was kept grounded. High DC voltage of up to −3 kV with respect to the ground was applied across the samples via electrodes for poling. The poling time was counted from the voltage turned on at the constant temperature required until heating of the samples was stopped, while the voltage was maintained during cooling-off.

The poled waveguide samples were characterized electrooptically using a fiber-based (single mode) Mach-Zehnder interferometer to measure induced nonlinear effect or linear electro-optic (LEO) coefficients. The LEO coefficients are given in equation below by measuring the phase shift (compared with a reference phase shift from $LiNbO_3$ phase modulator) from the poled waveguide samples.

$$r=\frac{\lambda t}{\pi V L n^3}\Delta\varphi, \tag{1}$$

where $\Delta\varphi=2\arcsin(\Delta V/V_{\text{contr}})$ is the induced phase shift of the poled waveguides, V_{contr} and ΔV are the maximum signal (peak-to-peak) induced from the phase shift of the commercial modulator and the modulated signal induced from the poled waveguide samples respectively under the same frequency. 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 1.

The poling temperature influence on the EO coefficient was studied and the corresponding results are shown in Fig.2, showing that maximum EO coefficients are obtained at optimum poling temperature (T_{opt}=357 °C) for the given waveguides with and without a charge trapping layer at a poling field of 208 V/μm. The EO coefficients decreased once the poling temperature shifted away from T_{opt}. The EO coefficient of the waveguides with a trapping layer is (0.093±0.001) pm/V, corresponding to $\chi^{(2)}$=(0.230±0.002) pm/V, which is about 20% greater than that without the trapping layer, which suggests that the distribution of the internal frozen-in field is changed and that its intensity is reinforced after poling as a result of adding the thin silicon oxynitride layer with charges trapped inside.

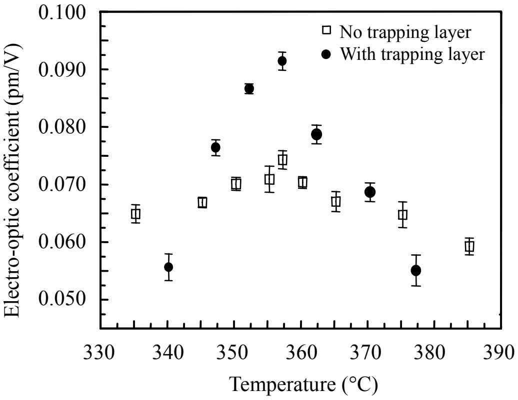

Fig.2 The dependence of EO coefficients on the poling temperature of the channel waveguides (TM mode) with and without charge-trapping layer. The waveguide samples were poled at –208 V/μm field intensity for 20 min in air environment

Though the induced $\chi^{(2)}$ value in waveguides is far below the value induced in the bulk silica by poling (Ozcan *et al*., 2004), this improvement is quite promising for further increase of EO coefficient in poled glass waveguides. The enhancement of the internal frozen-in field is attributable to the interface effect of the waveguides (Faccio *et al*., 2001; Arentoft *et al*., 2000). Mobile charges accumulate at the interfaces during the poling and are frozen there afterwards. Consequently, more charges trapped at the interfaces will strengthen $\boldsymbol{E}_{\text{int}}$ and favour the increased nonlinear effect. At the same time the $\chi^{(3)}$ values remain nearly unchanged before and after poling for all the samples measured by a Bragg grating technique (Marckmann *et al*., 2002). Increased optical nonlinearity and a gain of EO coefficient are therefore achieved via the stronger interaction between the internal field and the third-order nonlinearity of the waveguide material. For the waveguides without the trapping layer, the internal frozen-in field is built mainly from the limited charge accumulation at the interfaces.

The frequency response of the EO signals was measured as well from 5 to 100 kHz as shown in Fig.3. A basically flat response with frequency was obtained, which indicates no electrostrictive effect exists at low frequency. The flat frequency response is a technological advantage for the waveguide chips as active EO devices, such as polarization independent phase modulators and switches.

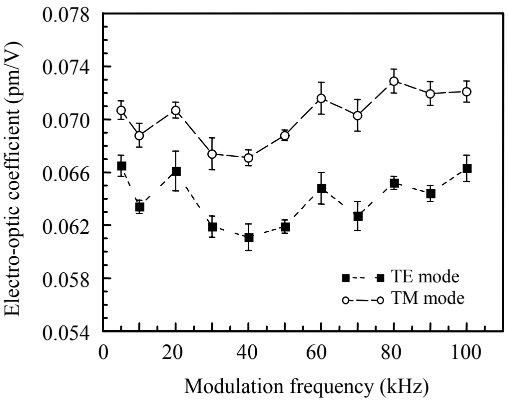

Fig.3 The frequency response of EO coefficients of the waveguide sample without the charge trapping layer poled at 357 °C and –2.5 kV for 30 min

CONCLUSION

In conclusion, poled waveguides show great potential to make active components or devices, large enough EO coefficients are necessary for them to achieve practical applications. The results presented here show that Ge-doped channel waveguides have promising properties showing a weakly polarization dependent EO effect, low linear loss and a flat frequency response; more important is an increased EO effect achieved by an optimized charge distribution around the core with a charge-trapping layer and via the interaction of a larger frozen-in field $\boldsymbol{E}_{\text{int}}$ with $\chi^{(3)}$ in the thermally poled silica waveguides. The presence of the thin silicon oxynitride layer does not have noticeable influence on the optimum poling temperature. The increased EO effect from the charge-trapping layer improves the prospects for fabricating EO components on a chip. Further studies are still needed to clarify the mechanism behind the optical nonlinearity in glass poling and to achieve further increase of the nonlinearity in poled glass waveguides, and to bring the EO coefficients of waveguides closer to the higher values obtained in poled bulk silica.

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