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Polarization selective electro-optic polymer waveguide devices by direct electron beam writing

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Abstract: A novel technique for the fabrication of polarization selective electro-optic polymer waveguide devices with direct electron beam writing was described. Birefringence induced by the electric field poling in the electro-optic polymer film was erased in the electron beam exposed regions. The formed waveguides had stronger confinement for the light polarized along the poling direction. High fabrication resolution on the 100 nm scale or smaller could be achieved. Fabrication of polymer polarizer and polarization selective microring resonators with this technique was reported. The highest polarization extinction ratio was measured to be 21.4 dB.

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1. Introduction

Polarization controlling presents a difficult challenge in the design and manufacture of integrated optical devices for the fiber optic communication systems. Standard single mode fibers used in the fiber optical communications do not preserve polarization and the light coupled from fiber to devices is in an arbitrary state of polarization, elliptically polarized in general. The polarization also fluctuates randomly on the time scales from a second to minutes, depending on the installation environments of the fibers [1]. Since most optical waveguide devices developed so far are polarization sensitive, i.e. their optical properties are different for the transverse magnetic (TM) and transverse electric (TE) modes, existence of these two orthogonal modes and random time variation of the polarization will cause signal fading and degrade device performance [2].

To eliminate these undesirable effects of polarization, the intrinsic approach is to make the optical components themselves polarization independent. Geometrical asymmetry and stress induced birefringences are two most significant factors that contribute to the polarization dependence of optical waveguides [3]. By carefully design and fine tuning of the waveguide refractive index profile, it is possible to obtain waveguide with nearly circular optical mode shape and eliminate the geometrical birefringence [4, 5]. Stress from the over-cladding or deposited metal layer on the waveguides can be used to balance the birefringence along the whole waveguide length or modify the birefringence locally and function as polarization compensators. Nevertheless it is difficult to completely eliminate birefringence and polarization variations in optical waveguides.

Polarization diversity is another effective method to achieve polarization independent devices. The idea is to split the TE and TM modes into two different optical paths [6,7]. Thus additional components of polarization splitters, converters and rotators need to be integrated together and additional fabrication steps are required.

The other approach is to remove one of the orthogonal modes in the waveguides. In addition to using an external polarizer, the waveguide itself can be made polarization selective. The metal clad waveguide [8], where metal layer has stronger absorption for the TM mode than the TE mode, and the anisotropic crystal clad waveguide [9], where birefringence of the crystal results in different refractive index contrasts of the two orthogonal modes, are two examples of the polarization selective waveguides.

Electro-optic (EO) polymers have large EO coefficient and low dielectric constant desirable for high speed EO modulators. For such advantages they are regarded as promising functional optical materials with impact to broad fields like telecommunications and defense [10]. EO polymers are intrinsically birefringent due to the preferential orientation of the second-order nonlinear optical chromophores in the polymer [11]. In this letter, we present a new method for making polarization selective EO polymer waveguide devices with direct electron beam writing. Poling induced birefringence in the electro-optic polymer films were erased with electron beam at the lateral cladding regions. Fabrication of electro-optic polymer waveguide polarizers and microring resonators are reported. As a standard nanolithography
tool, an electron beam lithography system can provide resolution on the nanometer scale. This contrasts with the poling induced waveguides [12,13], where fringe field at the poling electrode edges and lateral charge spreading at the layer interfaces result in a low resolution in the 1 μm scale, which is not capable to fabricate devices with fine features, such as microring resonators.

2. Experiments and results

Table 1. Electro-optic polymer waveguide material systems used in the experiments

| Material systems | Electro-optic polymer | Lower cladding |
|------------------|-----------------------|----------------|
|                  | Material              | Refractive index* | Poling temperature (°C) | Material | Refractive index* |
| 1                | 25% AJLS102 in 75PMMA dissolved in trichloroethylene (TCE) | 1.58 | 92 | OG125 | 1.46 |
| 2                | 25% AJLS102 in APC dissolved in cyclopentanone | 1.63 | 170 | UV16 | 1.51 |
| 3                | 25% YL124 in 950PMMA, dissolved in chlorobenzene | 1.56 | 115 | UV16 | 1.51 |

* Refractive indices were measured at the wavelength of 1550 nm and TE polarization with a prism coupler (Metricon 2010).

Fig. 1. Chemical structures of the electro-optic chromophores used in this study.

Three electro-optic polymer waveguide material systems were used in the experiments (Table 1). First about 3.6 μm low cladding layers of UV curable polymer UV16 (Master Bond Inc.) or OG125 (Epoxy Technology) were spin coated to the Si substrates and cured with UV exposure. The cured films were baked in vacuum oven at 65–85°C to evaporate any uncrosslinked monomers. For the electro-optic polymer waveguide layers, 25 wt% of chromophores AJLS102 [14,15] or YL124 [16,17] (Fig. 1) were mixed with APC (amorphous polycarbonate) or PMMA (polymethyl methacrylate) and dissolved in respective solvents given in Table 1. 75PMMA and 950PMMA have different molecular weights of 75,000 and 950,000. The guest host electro-optic polymer systems containing AJLS102 or YL124 have presented electro-optic coefficients r33 100–200 pm/V when an over 100 V/μm electric
poling field was applied. The formulated solutions were homogenized overnight in a rocker. After filtered through 0.2 \( \mu \)m syringe filters, the solutions were spin coated to the lower cladding coated substrates and prebaked on hotplates at 80°C for 1~2 mins. The films were then hard baked in a vacuum oven at 65~85°C for two days to completely remove residual solvents. The final electro-optic polymer film thickness was about 2 \( \mu \)m.

![Fig. 2. The index of refraction across a channel waveguide before poling (a), after poling (b), and after electron-beam patterning (c).](image)

To induce birefringence, the electro-optic polymer films were corona poled [18] in the air atmosphere near their glass transition temperatures (Table 1) for 10 min. The temperature was raised gradually from the room temperature with a rate of 5~10°C/min. The Si substrates were grounded and the corona was generated at the tip of a tungsten filament with 10kV DC high voltage applied. Alignment of the electro-optic chromophores was frozen to the direction of the electric field by cooling down the samples to room temperature with the poling voltage applied. This poling procedure induced anisotropy in the entire electro-optic film. The refractive indices for the light polarized along the alignment direction (\( n_{TM} \)) are increased and the refractive indices for the light polarized at the orthogonal direction (\( n_{TE} \)) are decreased, as shown in Figs. 2(a) and 2(b). Such poling induced birefringence \( \Delta n = n_{TM} - n_{TE} \) is known to be proportional to the square of poling parameter \( u = \mu E k T \), where \( \mu \) is the dipole moment of the chromophore molecules, \( E \) is the local electric field experienced by the dipolar molecules, \( k \) is Boltzmann’s constant, and \( T \) is the poling temperature in Kelvin [11].
Electron beam irradiation was then used to define the polarization selective waveguides in the poled electro-optic polymer film. Like thermal energy which randomizes the orientation of the chromophores in a poled EO polymer, energy of the electrons also agitates the chromophores and makes them to lose their orientational alignment. By exposing two strips separated by a small gap, a channel waveguide for TM polarization can be created in the gap region, and as an anti-guide for the TE polarization, as shown in Fig. 2(c). The electron beam writing system consisted of a FEI Sirion scanning electron microscope and a Nanometer Pattern Generation System. An accelerating voltage of 30 kV and a beam current of 5 nA provided a short writing time and high enough resolution. Different e-beam doses and waveguide widths were used in the study. The two strip areas outside the waveguides were exposed to electron beam to provide lateral confinement for the channel waveguide. The total width including waveguides and the two exposed strips was 50 μm (Fig. 3). To eliminate the cross-talk between the input and output fibers, the test waveguides were designed to have 90° bends of 500 bending radius.

![Electro-optic polymer](image)

**Fig. 3.** A schematic view of the polarization selective 90° bent waveguide defined by direct electron-beam writing.

For the measurement of polarization extinction ratios, the output of an erbium amplified spontaneous emission (ASE) broadband source with a wavelength range from 1520 to 1560 nm was polarized through an Agilent 8169A polarization controller, which consists of individually rotatable linear polarizer, half-wave plate, and quarter-wave plate and can synthesize any predetermined state of polarization. TM or TE light was respectively end coupled to one end of the waveguides through a polarization maintaining (PM) optical fiber. The output of the waveguide was lens coupled on to a photodetector of an optical power meter (Agilent 81623B). TM to TE polarization extinction ratio was calculated as the difference between the output powers of two polarization modes. Figure 4 shows the TM to TE polarization extinction ratios as functions of the electron beam doses for the three different EO polymers.

Electron beam randomizes the chromophores that had been preferentially aligned in the vertical direction during corona poling. The poling induced birefringence was erased and the regions of the electro-optic polymer films exposed to the electron beam were reverted to the unpoled state. This tends to form TM-pass waveguiding because there is a positive refractive index contrast between the poled waveguide region and unpoled (or electron beam depoled) lateral cladding regions for the TM polarized light but a negative index contrast for the TE polarized light [19]. An optimal dose exists to balance the two processes so that the TM polarization has low loss and the waveguide is an anti-guide to the TE polarization to achieve the highest polarization extinction ratio. Accompanying the de-poling process there is another process that also changes the refractive index of the EO polymer. It is the decomposition of the chromophores under the electron beam irradiation [20]. This process bleaches the electro-optic polymers (as could be observed under an optical microscope) and reduces both TM and TE indices in the electron beam exposed regions. Thus at higher doses when chromophore
decomposition becomes predominant, the waveguide can guide both TM and TE polarizations and the polarization extinction ratio is low. While at lower doses, the waveguide does not guide the TE polarization but the confinement is weak for the TM polarization. The propagation losses for both polarizations are high and the polarization extinction ratio is also low. Different host polymers and electro-optic chromophores have different electron beam sensitivities and poling induced birefringences and thus can have different optimal electron beam doses. Waveguide widths change the mode shape and contribute directly to the geometrical birefringence [3, 4]. For material system 1, the optimal electron beam dose is around 90–100 μC/cm², and the highest TM to TE polarization extinction is about 21 dB or higher (Fig. 4(a), waveguide width 7 μm). The optimal electron beam dose and the highest polarization extinction are around 1000 μC/cm² and 18 dB for the material system 2 (Fig. 4(b), waveguide width 5 μm). Those for the material system 3 are about 200 μC/cm² and 21 dB (Fig. 4(c), waveguide width 8 μm). Waveguide polarizers of high polarization extinction ratio have been made with all three material systems. The total loss of curved waveguides, including scattering and bend losses, is estimated around 15 dB/cm based on the insertion loss of the test samples.

Fig. 4. TM to TE polarization extinction ratios as functions of the electron beam doses for three different electro-optic polymer waveguide material systems: (a) 25% AJLS102/75PMMA on OG125. (b) 25% AJLS102/APC on UV16. (c) 25% YL124/950PMMA on UV16.
Prototype electro-optic polymer microring resonators with polarization selective property were also fabricated with the same technique. Exact position of the resonance peaks or dips are critical for a lot of applications of microring resonators like filters, modulators, switches and sensors. Random variation of the polarization in the optical fiber system shifts the resonance positions and degrades the device performance because of the intrinsic birefringence in most of the waveguide devices. If the ring waveguide itself is polarization selective or only support one polarization mode, the resonance wavelengths of the microring resonator will become insensitive to the external polarization fluctuation. The fabricated microring resonators had the basic structure of a single ring resonator coupled to a bus waveguide (Fig. 5). The radius of the circular sections is 500 μm. The waveguide width is 5 μm and the total width including waveguides and the two exposed strips is 20 μm. Racetrack shape microring resonator designs with different coupling gap sizes and coupling lengths were fabricated on the same wafer. The materials systems 2 and 3 and electron beam doses of 2000 μC/cm² and 700 μC/cm² were used to lower the bending loss in the rings.

![Fig. 5. A microscopic image of a polarization selective electro-optic polymer microring resonator fabricated with direct electron beam writing.](image)

Individual microring resonators were cleaved from the wafers to measure their transmission spectrum. The setup was similar to that for the measurement of polarization extinction ratio, only that the output from the device was fiber coupled to an optical spectrum analyzer (HP 70951B). Resonance spectra for both TM and TE polarizations were recorded (Fig. 6). No higher resonance modes presented in all the resonance spectra. This confirmed the single mode operation of the ring waveguides. The measured free spectrum ranges (FSR) agreed well with the perimeter ranges of the ring resonators. Different refractive index contrasts of TM and TE modes resulted in different propagation losses in the ring waveguides and different coupling conditions at the coupling regions. Thus with a certain range of coupling conditions, the microring resonator could support only resonances of one polarization (Fig. 6(a)). If the propagation loss difference was high enough, resonance signal of the TM polarization might overwhelm that of the TE polarization at the output (Fig. 6(b)). The relatively low resonance extinction is thought to be due to that the small index contrast causes high bending loss and makes the resonator under-coupled. By using larger ring radius, higher extinction and further suppression of the TE polarized signal is possible.
3. Conclusion

Polarization selective waveguide devices can be fabricated in electro-optic polymers by direct electron beam writing. The electro-optic polymer was first electric filed poled to induce birefringence in the film. Electron beam writing was then used to erase the birefringence at the exposed regions and provide lateral confinement for guiding the light polarized parallel to the direction of the poling field. Feature sizes on the scale of 100 nm or smaller could be resolved with a moderate electron beam writing system. Such level of resolution is desirable for many integrated optical devices. Three guest-host electro-optic polymers were used to fabricate polymer polarizers with this novel method. The highest TM to TE polarization extinction ratio was measured to be 21.4 dB. Possibility of electro-optic polymer polarization selective microring resonators with this technique was also proved.

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