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Patterned birefringence by photoinduced depoling in electro-optic polymers and its application to a waveguide polarization splitter

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Photobleaching by ultraviolet light at 410 nm wavelength of selected electro-optic poled polymers leads to birefringence which can be patterned on a submicron scale. Measurements at 1310 nm of the effect in an azo dye attached to poly(methylmethacrylate) is presented along with data showing the effect is not present in hardened cross linked polymer hosts. An integrated optic polarization splitter using the patterned birefringence has crosstalk at the transverse electric and transverse magnetic outputs of -23 and -27 dB, respectively, and excess loss 0.2 and 0.3 dB at 1310 nm.

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Poling induced birefringence (PIB) in an electro-optic (EO) polymer^{1,2} is due to the orientation of the EO chromophores along the direction of the poling electric field. The rod like chromophores are highly anisotropic and when aligned by a poling field perpendicular to the plane of the polymer film they create an uniaxial anisotropy with the optic axis along the poling field direction and with $n_e > n_o$, where n_e is the extraordinary index of refraction and n_o is the ordinary index of refraction. For light propagating in the plane of the film this means $n_{TM} > n_{TE}$. This orientation of the chromophores is also responsible for the second order nonlinear optical effect and the electro-optic effect in the films. Many of the EO chromophores are azo type dyes which show a strong photoisomerization from the *trans* to the *cis* isomer. If the poled films are irradiated by ultraviolet (UV) or short wavelength visible radiation which causes the *trans-cis* transformation, depoling of the films and the subsequent decrease in the electro-optic effect at room temperature has been observed in some polymers.^{3,4} This is explained by the increased rotational diffusion rate of the *cis* isomer. The long rod like *trans* isomer does not find enough free volume in the polymer to rotate and thus retains its angular alignment at room temperature. However, in the *cis* isomer state, the molecule is bent to a more spherical form and consequently requires less free volume to rotate. When in the *cis* state the room temperature thermal energy is able to cause relaxation of the poling alignment. The molecules return to the *trans* isomer by thermal relaxation but with their alignment randomized.

We report here the measurements of the change in the birefringence by UV exposure of poled polymer films due to *trans-cis* induced randomization of the alignment. The bire-

fringence of a poled film can thus be patterned to submicron resolution by exposure under a mask aligner. We also demonstrate that this UV induced depoling is not observed in denser cross-linked polymer hosts where presumably the *trans-cis* isomerization is inhibited.

The EO polymer is the Disperse Red 1 dye side chained attached to a poly(methylmethacrylate) (PMMA) backbone [poly(disperse red 1 methacrylate-co-methyl methacrylate); PMMA-DR1] from IBM-Almaden Research. The polymer film is prepared on a Si substrate with an Au layer used for the bottom electrode. Corona poling is performed at 113 °C. The poled polymer is then bleached successively by a UV mask aligner source at room temperature. The source has a spectral peak at 405 nm with an intensity of 10 mW/cm². The absorption peak of the PMMA-DR1 is at 470 nm. At each photobleaching (PB) step, the refractive indices for the transverse electric (TE) and transverse magnetic (TM) modes are measured with an ellipsometer at the wavelength of 1310 nm. Figure 1(a) shows the refractive index change of the poled EO polymer as a function of exposure energy. Before the poling, the refractive indices for the TE and TM modes are almost the same. After the poling, the TM mode index is increased and the TE mode index decreased. However with PB, the TM mode index is decreased and the TE mode index increased indicative of the randomization of the molecular alignment. We also monitored the r_{33} electro-optic coefficient at 1060 nm during the photobleaching. After the first photobleaching (18 J/cm²) the EO coefficient has decayed to 45% of the value immediately after poling. We believe that at higher exposure energy densities both the TE and the TM index will begin to decrease due to UV damage of the chromophores.

We also performed similar experiments on films of the EO polymer DR19 in a polyurethane thermoset trlinked polymer (TS-TL-PUR-DR19). The DR19 chromophore is very similar to the DR1 and also shows a strong *trans-cis*

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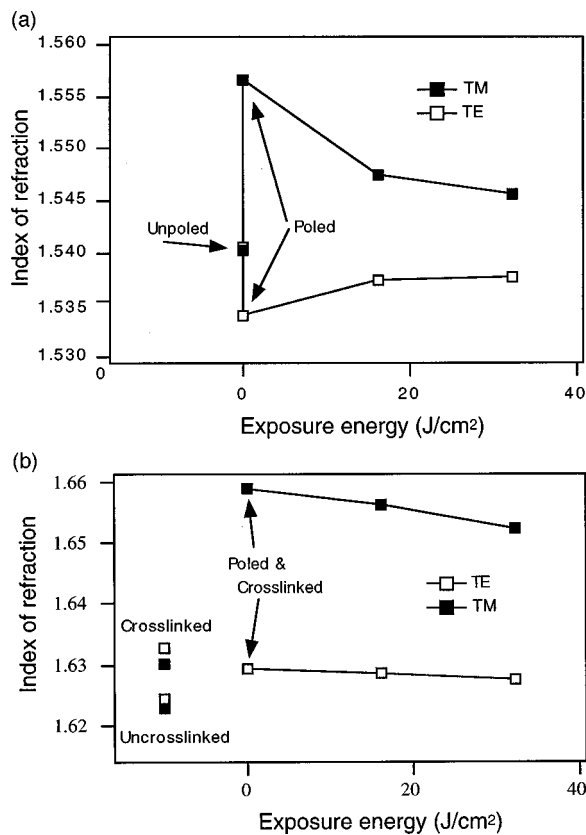


FIG. 1. Birefringence in a poled EO polymer at 1310 nm with photobleach energy, (a) PMMA-DR1. (b) TS-TL-PUR-DR19.

photoisomerization. The polymer system consists of a prepolymer with the DR19 covalently attached and a thermally excited cross linker. The films are simultaneously corona poled and thermally cross linked to achieve a dense three dimensional network with the chromophore preferentially aligned. Trilinking means that this material is a modified version of earlier TS-PUR-DR19⁵ in that not only are the two ends of the prepolymer cross linked but also the free end of the side chain attached DR19 chromophore is cross linked. After the cross linking the movement of the azo dye chromophore is restricted by the covalent bonds on each end and by the cross-linked polymer network. We believe the *trans-cis* isomerization is greatly inhibited since a chromophore bonded on each end cannot readily undergo the change in shape required by the *cis* isomer. Figure 1(b) shows the results of the photobleaching of the TS-TL-PUR-DR19. The uncross-linked measurement is for a film prior to heating when the film shows little birefringence. The cross-linked measurement is for a film which is completely thermally cross linked but not poled. The cross-linked film shows a slight increase in the index of refraction but little birefringence. After corona poling and complete cross linking the films show the typical poling induced birefringence with $n_{TM} > n_{TE}$. These films however do not show the UV photobleaching change in the birefringence but show only a slow decrease in both indices of refraction possible due to UV damage of the chromophores. We also measured the photobleaching of the r_{33} electro-optic coefficient measured at 1060 nm and observed a modest change to 80% of the initial after the first PB (18 J/cm²). We conclude that this decrease is not predominantly due to depoling since the mea-

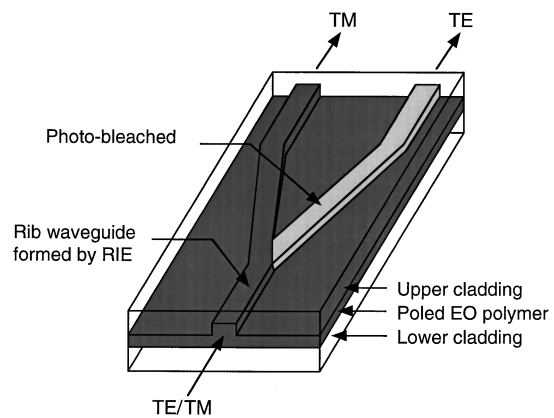


FIG. 2. Structure of the waveguide polarization splitter.

sured birefringence does not decrease. The only alternate explanation is chromophore damage.⁶

We have also demonstrated that this patterned birefringence in the PMMA-DR1 can be used to fabricate an integrated optical polarization splitter as shown in Fig. 2. Polarization splitters are used to separate the orthogonal polarization components of the guided waves and are essential components for coherent optical receivers and filters employing a polarization-diversity configuration.⁷ The corona poled EO polymer is used for the core and passive polymers are used for the upper and lower claddings. A Y-branch rib waveguide in the core layer supports both TE and TM modes. One arm of the Y branch is photobleached to reduce the refractive index for the TM mode and increase that for the TE mode. The operation of the splitter is based on the adiabatic transformation in the Y junction in which the input energy couples to the output guide with the highest effective index.⁸ Because of the PB, the input light is preferentially coupled to the bleached arm for the TE mode and to the unbleached arm for the TM mode. The index perturbation in the Y branch must be adiabatically introduced along the propagation direction in order to eliminate undesirable mode coupling between the local normal modes which causes the crosstalk. The PB erasure of the poling induced birefringence is well suited for this application because of the submicron resolution of the patterning.

A numerical simulation based on the beam propagation method and the effective index method has been used to design the splitter. In the analysis, the waveguide width is 5 μm , the branch angle is 5 mrad, and the gap between the two output waveguides is 50 μm . Figure 3 shows the calculated cross talk as a function of the effective refractive index change for the TM mode in the photobleached arm. Cross talk is defined as the ratio of the power in the expected polarization at an output to the power in the cross polarization in the same output. Here, the refractive index change for the TE mode, Δn_{TE} , and that for the TM mode, Δn_{TM} , are related as $\Delta n_{TE} = -1/3 \Delta n_{TM}$ which agrees with the data of Fig. 1. The analysis predicts that a cross-talk level of better than -30 dB can be achieved for both TE and TM modes for Δn_{TM} of 3×10^{-3} ; a change which can easily be achieved by PB.

The splitter was fabricated on a Si substrate with a gold bottom electrode. A 3.5 μm lower cladding (UV-15LV available from Master Bond Inc.) and a 2.5 μm core

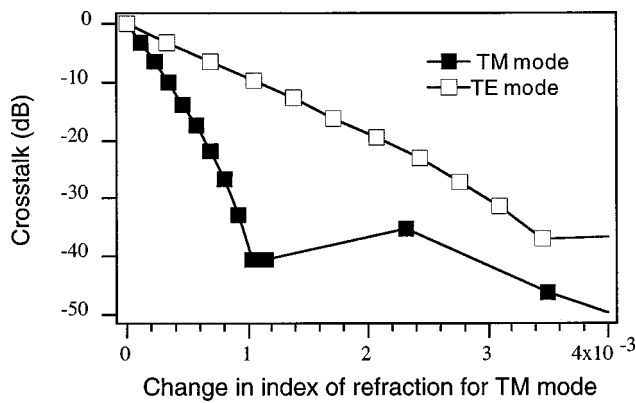


FIG. 3. Calculated cross talk as a function of the TM effective refractive index change in the photobleached arm.

(PMMA-DR1) are spin coated. After corona poling, standard lithography and reactive ion etching (RIE) in oxygen are used to form a single mode rib waveguide Y branch in the EO polymer. Straight reference waveguides were etched next to each Y branch. The upper $3.5\text{-}\mu\text{m}$ -thick cladding is UV-15LV. PB of one arm is performed at room temperature by aligning a pattern on the photomask. Finally, the endfaces are prepared by dicing. Controlled polarization 1310 nm light is butt coupled into the device from a single mode fiber. The output light is collected by a lens, passed through a Polarcor sheet polarizer, and measured by a power meter. A charge coupled device (CCD) camera was used to observe the single mode near field patterns at the output.

A series of PB steps were done on one device to optimize the performance and the results shown in Fig. 4. Excess loss is obtained by comparing the total throughput of the device for a given input polarization with that of adjacent reference straight waveguides. For a PB energy of $\sim 40\text{ J/cm}^2$, the cross talks for the TE and TM modes are -23 and -27 dB, respectively. The measured excess losses for the TE and TM modes are 0.2 and 0.3 dB, respectively. The total insertion loss is less than 5 dB for the total device length of 16 mm. For an exposure energy of more than 40 J/cm^2 , the cross talk for the TE mode is degraded, while that for the TM mode remains nearly the same. This may be because the

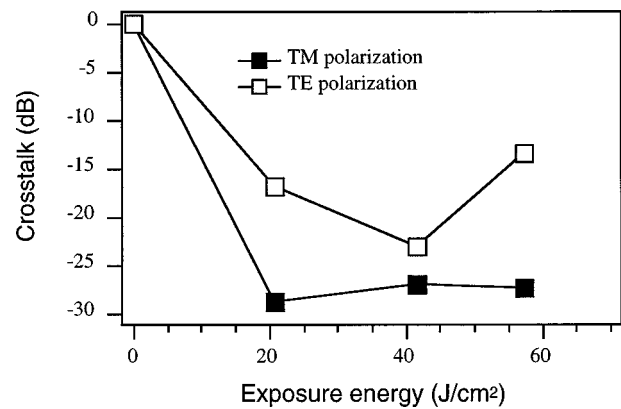


FIG. 4. Measured cross talk as a function of the photobleaching energy.

refractive index of the EO polymer is reduced as a result of the photochemical decomposition of the chromophores due to excessive PB.

We were able to independently confirm that the TE index of the PB films does increase by photobleaching. Waveguides fabricated by photobleaching the area outside the waveguide would support a TM mode but not a TE mode; the launched TE polarization went into slab modes outside the waveguide region.

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