

Poled electro-optic waveguide formation in thin-film organic media

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We describe a novel technique for the fabrication of electro-optic (EO) waveguides in integrated optic device structures employing organic EO materials. The technique combines the poling and waveguide formation steps by utilizing patterned poling electrodes and the induced birefringence associated with the poling process. Several prototype waveguide devices fabricated using this procedure are reported.

The electro-optic (EO) waveguide is an essential structure in integrated optic devices. Devices fabricated from such waveguides include mode converters,¹ modulators,² Y-branch interferometers,^{3,4} and directional couplers.⁵ Ti diffusion in LiNbO_3 is now a mature technology for fabricating integrated optic devices.⁶ Waveguides have also been fabricated in semiconductor materials such as GaAs⁷ and InGaAs/InP multiple quantum well structures.⁸ In recent years, organic and polymeric materials have emerged as a promising class of EO and nonlinear optical (NLO) materials.⁹ These organic materials can be formed into thin films, making them very useful in the integrated optics field.

The processes used to form thin films from organic EO materials, such as spin or dip coating techniques, do not usually produce EO films since the bulk structure is still centrosymmetric. A molecular alignment process, such as electrically induced poling,¹⁰ is needed to establish a noncentrosymmetric structure. To form three-dimensional waveguides in EO films, plasma etching¹¹ and channel filling¹² techniques have been utilized. In this letter, we describe a novel EO waveguide fabrication technique which combines the poling and waveguide formation steps by utilizing the induced birefringence associated with the poling process.

Two generic waveguide device structures are shown in cross section in Fig. 1. The first has electrodes above and below the film, while the second employs coplanar electrodes. In both cases, the EO layer is optically isolated from the electrodes by buffer or cladding layers. As shown in Fig. 1(a), before the poling step, the active molecules in what will be the EO layer are randomly oriented. After poling, the active molecules are partially ordered in areas defined by the electrodes, as shown in Fig. 1(b).

The partial ordering of the active molecules allows components of the second-order molecular nonlinearities to add, creating a region which exhibits the linear EO effect.¹⁰ Since most organic nonlinear molecules possess an anisotropic microscopic linear polarizability, the poled region also becomes birefringent.¹³ The poled regions are uniaxial, with n_e oriented along the direction of the local poling field. For materials in which poling induces positive birefringence, TM and TE waves propagating in vertical and transverse device structures, respectively, will experience a greater refractive index in the poled regions than in the surrounding unpoled regions, and so can be confined in the lateral dimension. Thus, by applying the poling fields using electrodes patterned to define the waveguide network, including both active and passive sections, no further patterning of the or-

ganic layer is needed to form the three-dimensional EO waveguide structures.

The devices can be fabricated in a number of ways depending on the type of EO material used and the final device structure required. For devices employing the vertical geometry, the upper electrode can be selectively removed over sections of the waveguides that must be inactive, or the entire upper electrode can be removed and a new electrode pattern deposited to address only the sections which must be active. For some EO layers, the upper electrode used during the poling/waveguide formation step can be deposited directly on the EO layer and then removed after the poling is accomplished. The devices can then be completed by depositing the upper buffer layer and a new upper electrode. It should also be possible in some cases to use electrodes with narrow (relative to the buffer layer thickness) gaps in them to pole the EO waveguides, and then use only certain sections to address the active portions of the device. In this later fabrication procedure, the poling/waveguide formation step would complete the device.

This technique of forming the EO waveguides in a single step has several advantages over other proposed fabrication procedures for organic waveguide devices. An obvious advantage is the simplification of the overall device fabrication

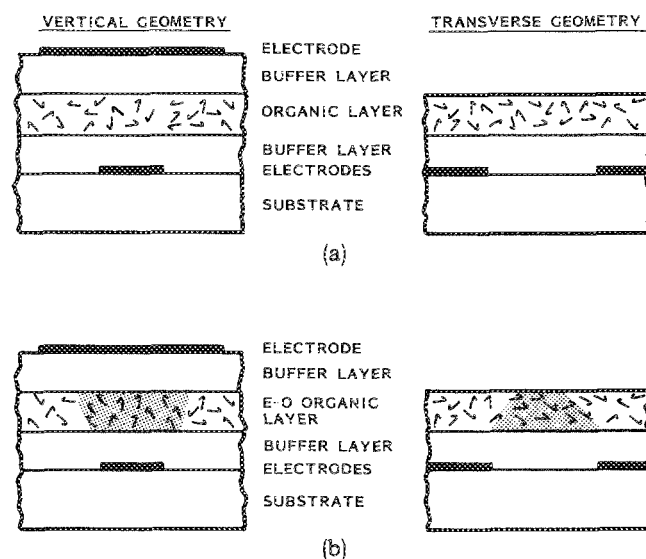


FIG. 1. Waveguide device structures (a) before and (b) after the poling/waveguide formation step.

process. A more important advantage is that the fringing of the poling fields in the buffer and EO layers tends to reduce the effects of electrode edge roughness on the roughness of the waveguide side boundaries. This is not the case when either fabricating channels in the substrate or etching the EO layer itself to form the waveguides. In fact, if the scale of the electrode edge roughness is small compared to the buffer layer thickness, the roughness of the side boundaries should be independent of the limitations of the photolithographic processes used to make the electrodes. This should result in low scattering losses from the waveguide side boundaries. Another advantage of this technique is that the waveguides that are formed guide only one polarization. One polarization therefore, can be selected from the incoming optical signal, facilitating the operation of subsequent devices, such as directional couplers or integrated interferometers, that operate most efficiently on light of a single polarization.¹⁴

Using this procedure, we have fabricated several prototype integrated optic devices in two different organic EO materials. The materials were PC6S and Celanese 22 (C22), both developed by the Hoechst-Celanese Research Company (HCRC). PC6S is a pendant side chain polymer that we have previously used as the EO layer in slab waveguide modulators,¹⁵ and C22 is a new HCRC proprietary material.

The induced extraordinary index change in PC6S due to poling is large: from 1.64 to 1.70 for unpoled to poled regions at 830 nm. These indices were calculated from coupling angles into slab guides of PC6S from LaSF9 prisms ($n = 1.83$). The index change for C22 was calculated from measured phase changes on double pass reflections through poled and unpoled regions of a C22 film. The induced extraordinary index increase in C22 is approximately 0.005 (1.575–1.58) from unpoled to poled regions.

Figure 2 shows the results of a computation using a beam propagation method¹⁶ for a normalized guide width of $5\lambda/n_{\text{eff}}$, where λ is the free-space wavelength and n_{eff} is the effective refractive index for light guided in the unpoled C22 layer. In Fig. 2(a) the indices in the poled and unpoled regions are the measured values for C22, while in 2(b) the

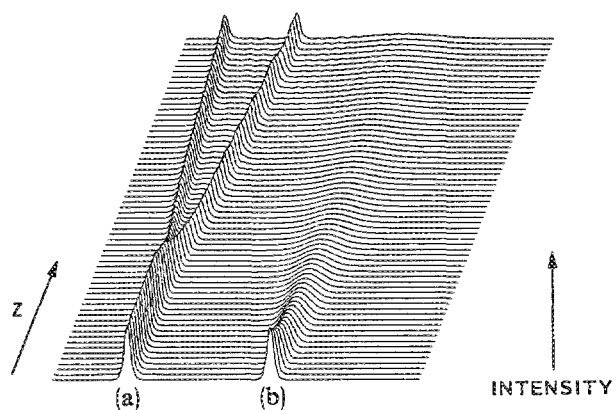


FIG. 2. Theoretical demonstration of beam confinement and splitting in a C22 film. (a) Optical signal launched in the z direction into a region selectively poled to define a Y-branch having a crossing angle of approximately 2.4° and widths of straight sections of $5\lambda/n_{\text{eff}}$. (b) Optical signal launched into an unpoled region demonstrating laterally unconfined propagation.

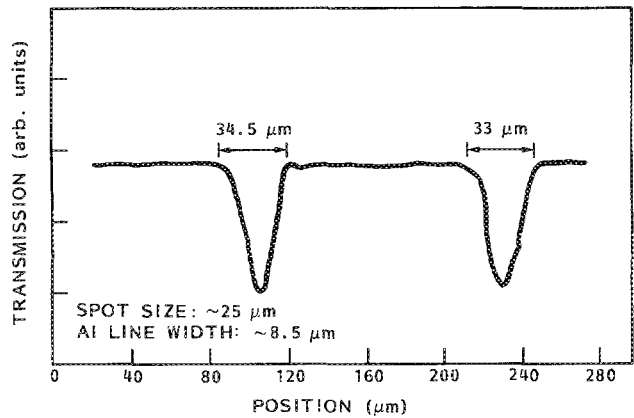


FIG. 3. Measured transmission ($\lambda = 632.8$ nm) through a PC6S structure containing two adjacent poled waveguides (each of vertical geometry) as a function of position. The beamwidth was approximately $25\ \mu\text{m}$. No birefringence is observed beyond the $8.5\text{-}\mu\text{m}$ -wide aluminum poled electrodes.

index is 1.575 uniformly. As expected, strong confinement is predicted.

A potential problem with this technique may be loss of resolution due to lateral charge spreading at the layer interfaces. This has not been a problem, however, in the structures we have fabricated. Figure 3 shows the results of an experiment in which a $25\text{-}\mu\text{m}$ -diam beam ($\lambda = 632.8$ nm) was scanned across two adjacent $8.5\text{-}\mu\text{m}$ -wide aluminum electrodes above which poled waveguide structures with PC6S as the EO layer had been fabricated. The aluminum electrodes partially blocked the beam as it passed over them; but no birefringence, as can easily be seen when scanning across poled slab waveguides formed on substrates coated with transparent conductors, was detected beyond the electrodes.

To fabricate the prototype devices, aluminum lower electrodes defining Y-branch interferometers and directional couplers were formed on glass substrates using standard deposition and photolithographic techniques. The dimensions of these electrodes were chosen to facilitate the evaluation of the poling/waveguide formation process and so were not scaled to optimize the performance of the completed devices made from the different materials. A $2\text{--}3\text{-}\mu\text{m}$ -thick UV-curable coating was deposited on each substrate to form the lower buffer layer. A $2\text{-}\mu\text{m}$ -thick layer of EO material was then deposited by spin coating.

Initial waveguide fabrication work was done with PC6S. A Y-branch interferometer was built by evaporating a gold

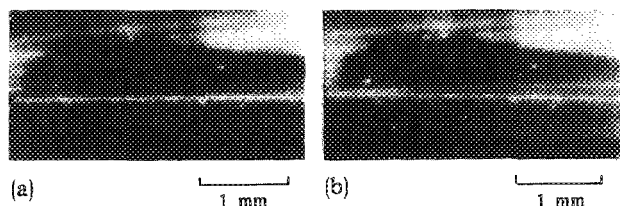


FIG. 4. Experimental verification of beam confinement and partial switching in a poled Y-branch interferometer in C22: (a) 120 V applied, and (b) 65 V applied. The remainder of the gold upper electrode can be seen above the waveguides.

electrode directly onto the PC6S, poling the waveguide pattern at 90 °C for 5 min with an electric field of 100 V/ μm in the EO layer, etching off the electrode with dilute Aqua Regia, and finally bonding a piece of indium-tin-oxide-coated glass over one arm of the interferometer with a 3- μm -thick layer of epoxy. The epoxy also served as the upper buffer layer. Prism coupling was used to inject 830 nm light into the device. Guiding was observed along each arm, and modulation of the output beam was detected.

In addition to a Y-branch structure of the same basic design as that built using PC6S, a prototype directional coupler was fabricated using C22. The electrode that defined the final waveguide pattern consisted of two 7- μm -wide sections brought to a 13- μm -wide, 1-cm-long common section at a crossing angle of 3°. The common section was followed by a symmetric arrangement of two more 7- μm -wide sections. The overall length of the electrode was 3.8 cm. To build this device, a 3- μm -thick polysiloxane upper buffer layer was deposited onto the C22 layer by dip coating. A gold upper electrode was then deposited and the waveguide pattern was poled at 105 °C for 30 min with an electric field of 90 V/ μm in the C22 layer. The device was completed by removing the gold electrode over the incoming and outgoing waveguides.

Partial switching of 830 nm light from one output arm to the other is shown in Fig. 4. Prism coupling was used to inject light into the lower input arm (not shown). An applied voltage of 120 V produced the bar state shown in Fig. 4(a), and an applied voltage of 65 V produced the partial cross state shown in Fig. 4(b). Complete switching was not observed, but this is not surprising due to the large crossing angle and the nonoptimum waveguide dimensions.

In conclusion, we have developed a novel technique for fabricating EO integrated optic devices in thin-film organic

media. The technique should be applicable to many EO and NLO organic systems, produce waveguide structures with very smooth sidewalls, and simplify the overall device fabrication procedure.

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