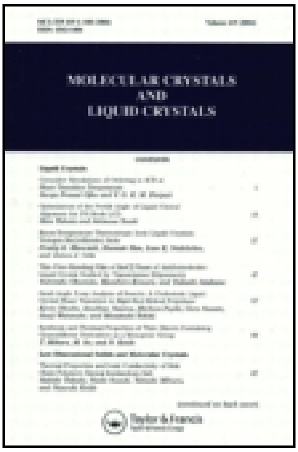

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DESIGN AND FABRICATION OF NONLINEAR OPTICAL POLYMER WAVEGUIDE DEVICES

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Abstract Issues related to the design of poled electro-optic polymer waveguide have been analyzed in terms of modulation voltage, optical loss due to metal electrode and mode size. The analysis suggests a couple of general guidelines for the device fabrication. Firstly, asymmetric structure gives better performance than symmetric structure in term of modulation voltage and mode size, where the refractive index of one of the buffer layers is close to the guiding layer and that of the other layer is much smaller than the guiding layer, by more than 0.1. Secondly, the guiding layer needs to be fabricated as thick as possible within the range of the single mode operation for a given material system to obtain lowest possible modulation voltage under a given limit of electrode associated loss. Electro-optic modulators fabricated using the photobleaching technique supported the guidelines.

INTRODUCTION

Extraordinary nonlinear optical (NLO) and electro-optic (EO) properties of certain organic materials have attracted large interest for many years. Organic EO materials offer significant advantages over conventional inorganic materials such as $LiNbO_3$ or compound semiconductors in the several key areas including large EO coefficients, low dielectric constant, fabrication flexibility and simple processibility which lead to high bandwidth modulators and high integration densities of many functional devices either in monolithic or hybrid forms on a single wafer [1,2].

Much research effort has been poured into molecular engineering to improve the material properties such as linear optical, nonlinear optical properties and thermal stability with great success during the last several years[3-6]. Potential of nonlinear optical polymer devices has been demonstrated with prototype devices. Polymeric waveguide devices such as electro-optic modulators with tens of GHz [7-8], multilevel modulators[9] and switches[10], and hybrid integration of polymer external modulators with semiconductor laser diodes[11] have been reported.

With large success of materials research and demonstration of the potential of nonlinear optical polymer waveguide devices it is appropriate time to consider the detailed design of polymer waveguide to fully utilize the material property for the devices. In this paper we will describe the factors to be considered for the design of polymer waveguide devices and compare with the fabricated ones.

WAVEGUIDE DESIGN

To analyze the issues involved in the design of polymer waveguide we select a typical electro-optic device whose cross sectional geometry and notation used for the design are shown in Figure 1. Devices poled with parallel plate electrodes is considered so that electro-optic coefficient along the direction normal to the substrate defined as γ_{33} is the largest. Gold layer deposited on silicon wafer was used as the ground electrode. The guiding layer with thickness of d_g and refractive index of n_g is separated from the ground and top modulation electrodes by lower and upper buffer layers, respectively. The thicknesses and the refractive indices of the upper and lower buffer layers are noted as d_u and n_u, and d_l and n_l, respectively. If one has a suitable EO material for device fabrication, suitable buffer layers should be selected first. For the demonstration purpose, we used Poly(4-dimethylamino-4'-nitro stilbene methacrylate (P2ANS) - co - methylmethacrylate. (MMA)) with the composition of (50/50) as the guiding layer whose refractive index is 1.624 at 1.3 μm [12]. Lower buffer was selected as the same material with slightly lower chromophore composition whose refractive index is 1.609 for mode size control. The choice of the material as a buffer layer will become clear later. Refractive index of the upper cladding layer varied from 1.45 to 1.61 with materials in mind such as polysiloxane, PMMA, NOA61, AZ4562 and lower buffer material whose refractive indices are 1.45, 1.480, 1.525, 1.59 and 1.609, respectively.

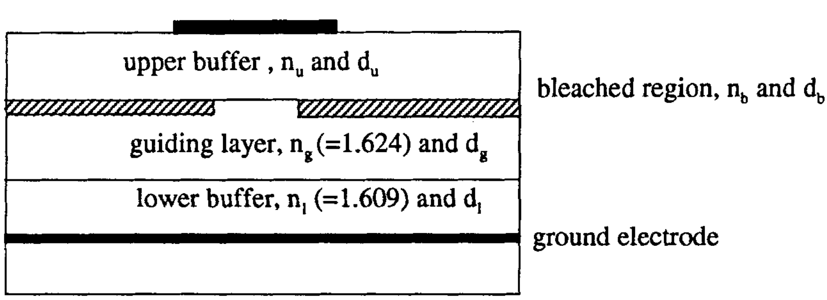

Figure 1 Cross sectional geometry and the notation used for waveguide design

Before any design of channel waveguide, proper thickness of the guiding, lower and upper buffer layers should be determined by analysis. The thickness range of the guiding layer is obtained from the condition of single TM mode operation. This can be calculated from simple dispersion relations. Figure 2 shows the dispersion relation calculated by the effective index method for the different material systems at 1.3 μm wavelength. The guiding layer thickness supporting the single mode operation increases as the asymmetry of the refractive index between the lower and upper buffer layers increases.

The next step in the design is to find the thickness of low and upper buffer layers. These parameters affect two device operation parameters: modulation voltage and optical loss due to metal electrodes. The optical loss can be lowered by using thicker buffer layers. However thicker buffer layers result in higher modulation voltage because the latter is inversely proportional to the total thickness of the waveguide. There exists trade off between the optical loss and the modulation voltage. The electrode associated optical loss can be calculated by performing complex mode analysis on the waveguide structure of Figure1.The optical loss depends not only on the thickness of the buffer layers but also on the thickness of the guiding layer because the optical power confined in the guiding layer depends on the guiding layer thickness. Figure 3 shows the total waveguide thickness to have the

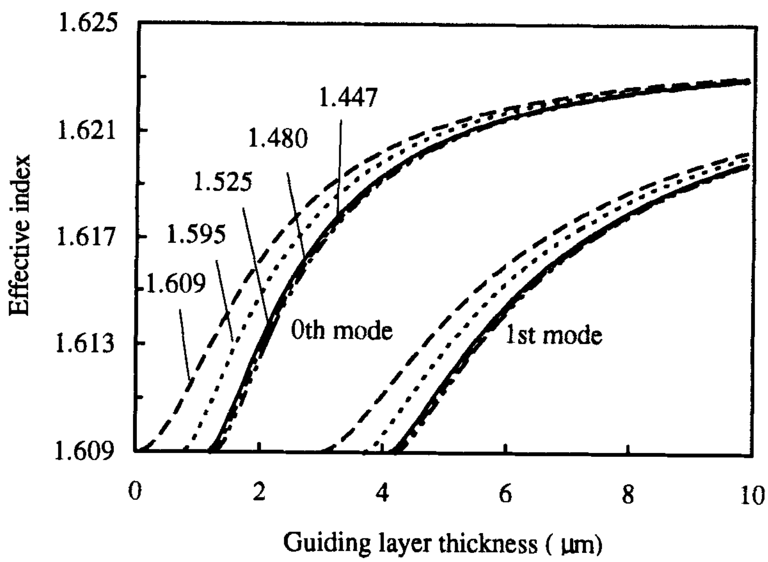

Figure 2 Dispersion relation of the device in Figure 1 as a function of guiding layer thickness for different refractive index of the upper buffer layer

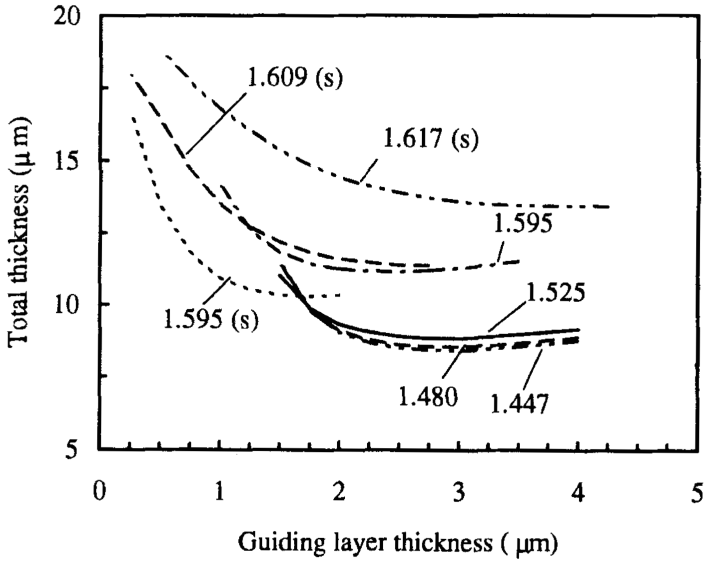

Figure 3 Total thickness of the waveguide in Figure 1 required to have electrode associated loss less than 0.1 dB/cm for different refractive index of upper buffer layer. Symmetric waveguides indicated by (s) beside the refractive index are included for comparison.

loss lower than the required limit, for instance 0.1 dB/cm, as a function of guiding layer thickness within the single mode operation range. It is interesting to note that as the guiding layer get thicker the total thickness of the waveguide required to achieve a certain optical loss decreases initially and becomes almost constant above a certain range. Thinner waveguide is possible with lower refractive index buffer material.

In general buffer layers are not electro-optic materials so that externally applied voltage to the waveguide induces the refractive index change of the guiding layer only. Since the wave propagating a waveguide feels the effective index change ΔN induced by the refractive index change Δn of the guiding layer it is important to take into account the modulation efficiency defined by $\Delta N/\Delta n$. It is calculated again from the dispersion relation against the guiding layer thickness and is shown in Figure 4. The modulation efficiency increases again with increasing guiding layer thickness. This is consistent with expectation because the power confined in the guiding layer increases as the guiding layer thickness increases.

Modulation voltage is a primary concern of a modulator. Since the modulation voltage can be expressed by

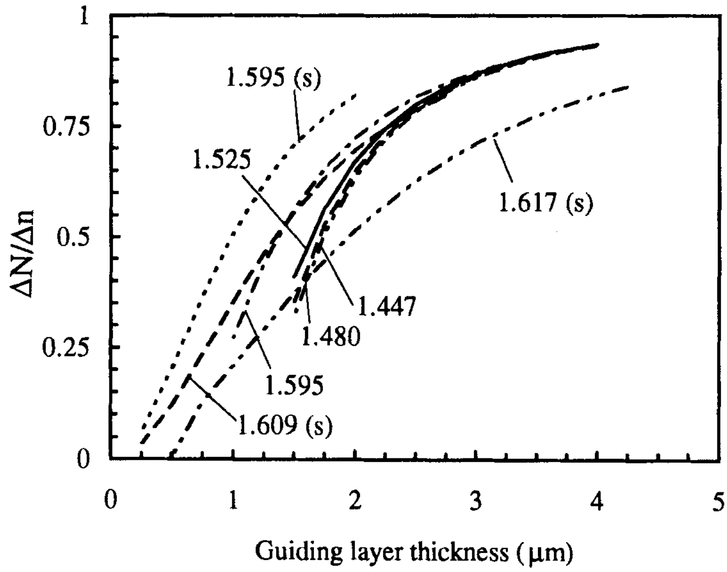

Figure 4 Modulation efficiency for different refractive index of upper buffer layer as a function of guiding layer thickness. Symmetric waveguides are included.

$$V_\pi = \left(\frac{\lambda}{n^3 \gamma_{33}}\right)\left(\frac{\Delta n}{\Delta N}\frac{d_{tot}}{L}\right)$$

where λ is the wavelength of the light, n the refractive index of the guide material, d_{tot} the total thickness of the waveguide and L the length of the modulation electrode. The former part in the right hand side of the equation is related to material parameters and the later to device design factors. For a modulator to have the lowest possible modulation voltage one needs to maximize the figure of merit $(\Delta N/\Delta n)/d_{tot}$ under a given loss limit due to electrode. The factor is plotted in Figure 5. It can be clearly seen that lower modulation voltage can be attained with thicker guiding layer for a given material system. Lowering the refractive index of the upper buffer layer (or increasing the asymmetry between two buffer layers) up to a certain point is beneficial to achieve low modulation voltage. However, it does not change much if the asymmetry is over a certain point (0.1 in our system).

Mode size of the guided light is an important factor in terms of the coupling loss with optical fiber whose mode is approximately 10 μm. In Figure 6 is displayed the calculated mode size of symmetric waveguides as well as the asymmetric waveguides for comparison. Figure 6 shows that exact mode matching with fiber is not possible even with the refractive index difference of 0.008 between the guiding and the

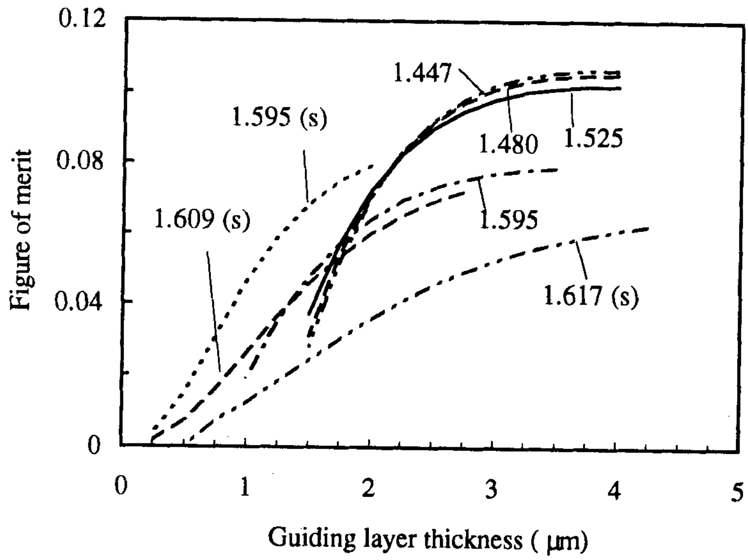

Figure 5 Figure of merit of electro-optic modulators for different refractive index of upper buffer layer as a function of guiding layer thickness.

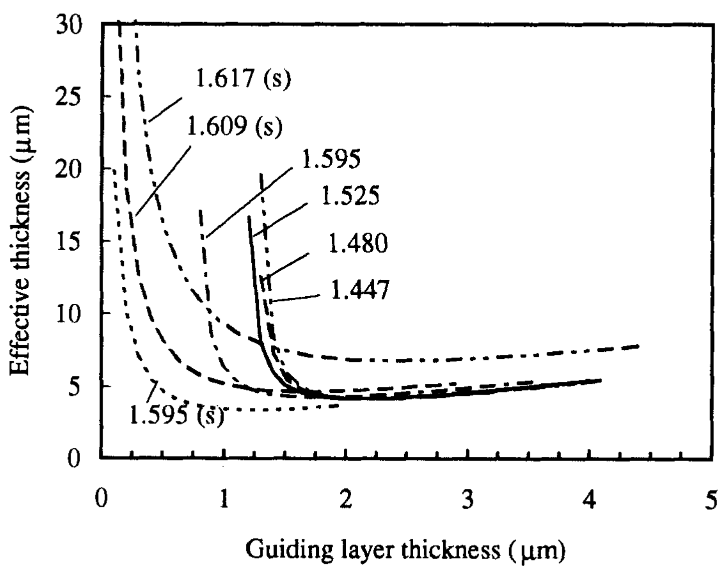

Figure 6. 1/e TM mode size of symmetric and asymmetric waveguides in the vertical direction for different refractive index of upper buffer layer as a function of guiding layer thickness.

cladding layers of the symmetric waveguide. However modulation voltage increases significantly with increasing the refractive index of the buffer layers as appeared in Figure 5. Decreasing the refractive index of the symmetric buffer layers from 1.617 to 1.595 results in rapid decrease of the mode size to below 4 μm with only marginal improvement of modulation voltage. One way of maintaining the reasonable mode size and keeping the figure of merit of the modulation voltage high at the same time is to use an asymmetric structure. Mode size changes little as the refractive index of one buffer layer varies from 1.609 to 1.45 as long as that of the other buffer layer is maintained constant as manifested in Figure 6. In other word, one can control the mode size of the waveguide by just one buffer layer. The other buffer material can be selected to decrease the modulation voltage as described before, that is, the material with n lower than 1.52.

In summary, we can draw some general guidelines for polymer waveguide design from the above analysis: Firstly, one needs to fabricate the guiding layer as thick as possible within the region satisfying the single mode operation condition to obtain the lowest possible modulation voltage under a required maximum electrode-associated loss. Secondly, the refractive index of one buffer layer needs to be close to that of the guiding layer to have mode size matching to optical fiber. On the other hand the refractive index of the other buffer layer needs to much smaller than that of the guiding layer to lower the modulation voltage. In the fabrication we selected the lower buffer with n=1.609 and the upper buffer with n=1.525.

Next step in the design is to form the channel waveguide. Photobleaching technique was considered for the design because of its simple processibility and controllability. Even though photobleaching of a nonlinear optical polymer results in graded refractive index profiles[11,12], step index profile was assumed to be formed for simplicity. The waveguide structure in Figure 1 was used for the design. Effective index method was also utilized again in the lateral direction. Since the effective index in the bleached region changes as the bleaching proceeds, the effective index difference between the channel region and the bleached region changes with bleaching depth. Following the nearly same procedure for TE mode as the slab waveguide described before, maximum channel width allowing the single mode operation in the lateral dimension can be calculated as shown in Figure 7. 3.8 μm thick guiding layer and the refractive index of 1.569 for the bleached region were used in the calculation.[12] The mode size in the lateral direction should be calculated to choose the bleaching depth and the channel width and is shown in Figure 8. From the calculation bleach depth of 1-1.5 μm was selected for the fabrication of the electro-

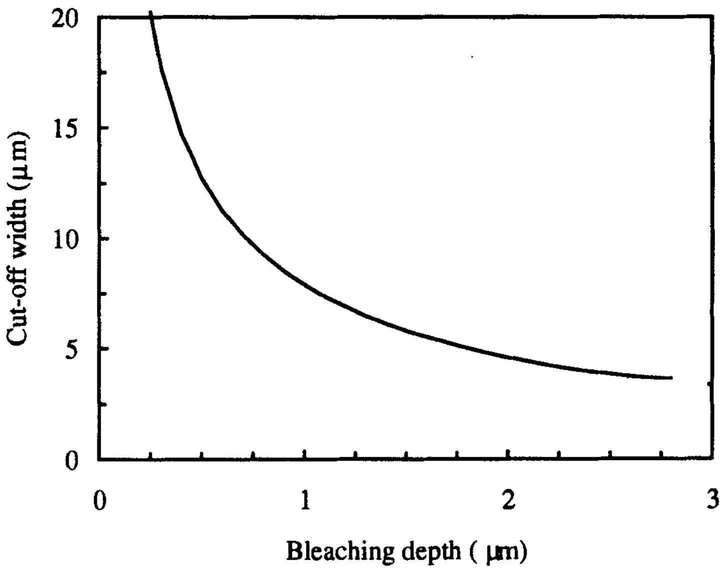

Figure 7 Cut off channel width for single mode operation as a function of bleaching depth for the guide thickness of 3.8 µm. n_g=1.624, n_l=1.609, n_u=1.525 and n_b=1.569 were used for the design.

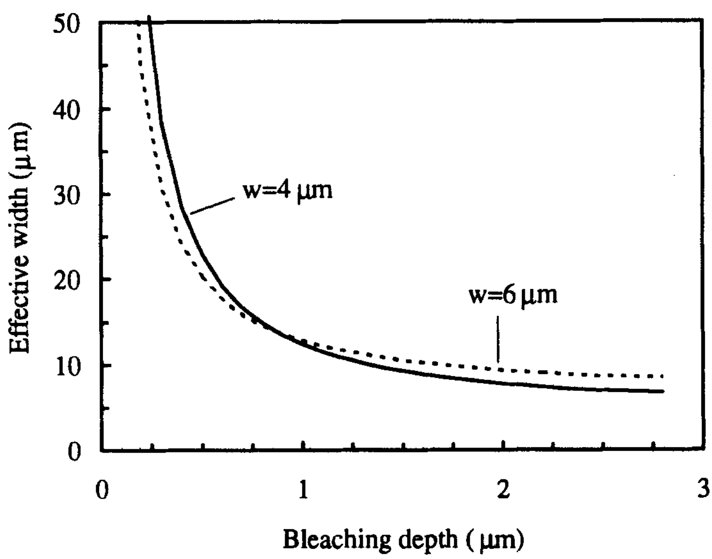

Figure 8 1/e TM mode size in the lateral direction against bleaching depth for two different channel widths of 4 and 6 µm optic modulator.

Birefringence of the guiding layer induced by poling was not considered in the analysis. More thorough analysis requires to consider it. However, the description made in the analysis is still valid because the qualitative description is not affected by including the birefringence effect. It changes the numerical values only.

FABRICATION OF ELECTRO-OPTIC MODULATOR

Materials used for the guiding layer was described before. The material was supplied from Hoechst Celenese. Electro-optic coefficient of 30 pm/V is achievable with the material when the side group is sufficiently oriented by electric field poling. Refractive index of the material was measured by prism coupling technique to be 1.624 without bleaching and 1.569 when fully bleached, respectively. The same material with different composition of (35/65) was used as a lower buffer layer whose refractive index is 1.609. Two different kind of materials were used as the upper buffer layer, a photoresist purchased from Hoechst (n=1.595) and hard optical epoxy (1.525) for the comparison purpose. When the photoresist was baked at high temperature it was not reactive any more. Gold coated Si wafer was used as a substrate. Lower buffer and guiding layers were successively coated on the substrate. Channels were created by irradiation of UV light through a waveguide mask using a mask aligner (Karl Suss MJB 3). After the channel waveguide formation upper cladding layer was spin coated. Electrode poling was applied for the alignment of the chromophore after completion of the waveguide structure at the temperature of 135 °C. Finally metal electrode was formed on the waveguide using the Mask aligner. The metal electrode was formed on only one arm of the Mach - Zehnder interferometer. 1.3 μm light from laser diode was coupled to the cleaved devices by end fire coupling. Vidicon was used to analyze the modulation characteristics and the mode pattern.

RESULTS AND DISCUSSION

Two devices were fabricated for comparison. The structural parameters and the performance of the devices are summarized in Table I. Device 1 is close to the optimum device structure suggested in this paper and device 2 is not optimized. Hard optical epoxy and hard cured photoresist are utilized in device 1 and 2 as the upper buffer layer, respectively. 4 μm channel waveguide was used for the characterization. Device 1 shows superior device performance to device 2 in almost every device

TABLE I The structural parameters and the performance of two electro-optic modulators

	Device 1	Device 2
Guide thickness (μm)	3.8	2
Low buffer thickness (μm)	3.5	4
Upper buffer thickness (μm)	1.5	4
Refractive index of upper buffer	1.525	1.595
Total thickness (μm)	8.5	10
Bleached depth (μm)	1.3	1.1
Electrode length (mm)	14	14
Poling voltage (V)	850	1100
Poling field (MV/cm)	1	1.1
Modulation voltage (V)	18	30
Extinction ratio (dB)	>9	8
1/e Mode size (μm)		
lateral direction	8.1	7
vertical direction	5.5	3.5
Electro-optic coeff. (pm/V)		
predicted	15	17
observed	10	14.5

characteristics; lower modulation voltage, higher extinction ratio, larger mode size in the vertical direction. Even though total thickness of the device 1 is thinner than device 2, the mode size of the device 1 is larger than that of the device 2 which is beneficial to optical fiber coupling. Extinction ratio of the device 1 is especially poor. This may come from optical loss associated with the metal electrode which is on only one arm. This low extinction ratio indicate that 4 μm thick buffer layer is not enough to get low enough electrode associated optical loss even though 1.5 μm thick buffer layer in the device 1 is enough to get low enough loss without sacrificing any device characteristics. This fact demonstrates the importance of the proper selection of buffer materials.

CONCLUSION

Issues related to the design of poled electro-optic polymer waveguide have been analyzed in terms of modulation voltage, optical loss due to metal electrode and mode size. The analysis suggests a couple of general guidelines for the device fabrication. Firstly, asymmetric structure gives better performance than symmetric one in term of the modulation voltage and the mode size, where the refractive index of one of the buffer layers is close to the guiding layer and that of the other layer is much smaller than the guiding layer, by more than 0.1. Secondly, guiding layer needs to be fabricated as thick as possible within the range of the single mode operation for given material system to obtain lowest possible modulation voltage under a given limit of electrode associated loss. Electro-optic modulators fabricated using the photobleaching technique supported the guidelines.

ACKNOWLEDGMENT

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