

# Single-mode polymer waveguide modulator

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We report herein the first single-mode polymer waveguide modulator which can be formed on any surface regardless of its conductivity and refractive index. These include semiconductor, conductor, and insulator surfaces. The tunability of the refractive index of the polymer film allows us to shift the guiding layer from a stepped index profile to a graded index profile. The phase-matching condition for optical power transfer is achieved through current-induced index modulation. Thirty-six dB extinction power ratio, which includes 3 dB absorption loss and 33 dB phase-matched cross coupling, was observed with a current injection density of  $\sim 1.8 \mu\text{A}/\mu\text{m}^2$ . Unlike the conventional symmetrical dual channel coupler, the disparity of the collinear waveguide pair provides us with a much larger dynamic range of waveguide dimension suitable for generating the required phase-matching condition and thus easing the requirement of waveguide fabrication.

We are reporting for the first time a novel collinear electro-optic modulator on a polymer microstructure waveguide which can be constructed on any smooth surface including semiconductor, conductor, and insulator. The feasibility of constructing high quality waveguides was first confirmed on Si, GaAs,  $\text{Al}_2\text{O}_3$ , BeO, PC board,  $\text{LiNbO}_3$ , etc.<sup>1,2</sup> Formation of a universal polymer microstructure waveguide was made possible by tuning the guiding layer index profile from stepped index to graded index through a mass perturbation method. The general shape of the index distribution is shown in Fig. 1. Graded index profiles from nearly Gaussian to nearly linear, which were determined by using the IWKB method, can be produced by employing such a method.

A single-mode collinear modulator was made based on the heterowaveguide structure shown in Fig. 2(a). The substrate can be any thin film of interest, for example, GaAs,  $\text{LiNbO}_3$  etc. The first layer is a waveguide with multiple modes. Formation of the waveguide was carried out by tuning the index so that the substrate index does not influence waveguiding on the low-index polymer film. The second layer is a thin, transparent semiconductor film ( $\sim 100 \text{ nm}$ )  $\text{In}_{1-x}\text{Sn}_x\text{O}_y$  with an index of refraction of 1.74 at  $0.6328 \mu\text{m}$  wavelength. The film refractive index can be modulated by current injection. Finally, a single-mode polymer waveguide was coated on top of the semiconductor film. The refractive index distribution is schematically shown in Fig. 2(b). The measured effective indices of these two collinear waveguide are shown in Fig. 3. There are ten modes on the multimode guide. Note that the effective index of the multimode waveguide was immediately measured after the formation of  $\text{In}_{1-x}\text{Sn}_x\text{O}_y$  film. The difference of the mode effective indices between TE (transverse electric) and TM (transverse magnetic) modes was not observed. The propagation loss of the single-mode polymer waveguide was measured to be within  $1 \pm 0.5 \text{ dB/cm}$ .

The explanation of the mechanism for intensity modulation is as follows: The first multimode waveguide was made thick enough to support a large number of guided modes. The second single-mode waveguide was made so

that the mode index was within the numerical value of the effective indices of the multiple mode waveguide, i.e.,

$$N_{m_{i-1}} < N_{\text{eff}} < N_{m_i}, \quad (1)$$

where  $N_{\text{eff}}$  is the effective index of the single-mode waveguide and  $N_{m_{i-1}}$  and  $N_{m_i}$  are the effective indices of the  $i-1$ th and  $i$ th modes, respectively. The change of refractive index caused by current injection was previously reported by various research groups.<sup>3-7</sup> The index modulation generated by current injection is polarization independent and can be two orders of magnitude higher than the linear electro-optic effect. Transferring of the guided wave from single-mode guide to multimode guide and vice versa was fulfilled by shifting the film index of  $\text{In}_{1-x}\text{Sn}_x\text{O}_y$  through current injection. An electrical current is injected into the semiconductor layer so that the phase matching condition

$$N_{\text{eff}} = N_{m_i} \quad (2)$$

can be achieved. It is to be noted that the coupling constant  $K$  is defined by<sup>8</sup>

$$K = \langle \Psi_s | i\omega \Delta \epsilon(x, y, z) / 4 | \Psi_{m_i} \rangle, \quad (3)$$

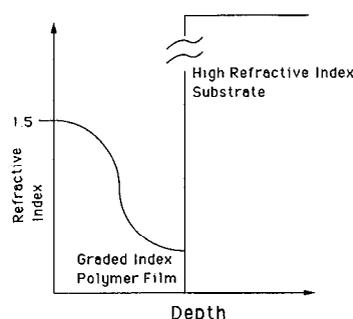


FIG. 1. General shape of the graded refractive index profile of polymer waveguide.

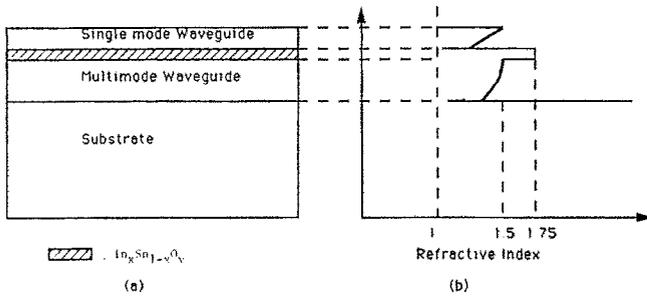


FIG. 2. (a) Heterostructure of the polymer waveguide modulator, (b) Schematic of the refractive index distribution of the multilayer structure.

where  $\omega$  is the angular frequency of the optical wave,  $\Delta\epsilon$  is the difference of the dielectric constants between the waveguide and the cladding, and  $\Psi_s$  and  $\Psi_{m_i}$  are the mode profiles of the single mode and the  $i$ th mode of the multimode waveguide, respectively. The cross product is performed over the waveguide interaction region. Deviation from the criterion set by Eq. (2) will automatically generate a mismatch phase term in Eq. (3) which, depending upon the quantity of mismatch, may result in a zero coupling coefficient. It is clear from Fig. 3 that the maximum index modulation needed to generate the phase matching condition is

$$\Delta n = (N_{m_{i-1}} - N_{m_i}). \quad (4)$$

It is to be noted that, due to the refractive index distribution displayed in Fig. 2(b), the current-induced index modulation mainly shifts the effective indices of the multimode guide. Equation (4) explains the reason for the requirement of a highly multiple mode waveguide. To reduce the current injection and therefore, the power consumption, the mode separation of the multimode waveguide needs to be carefully controlled.

The device structure in Fig. 4 illustrates each individual component involved. The interaction length is 1 cm. The current is injected into the  $\text{In}_{1-x}\text{Sn}_x\text{O}_y$  film through the ohmic contact and the optical wave is coupled into the single-mode waveguide through a prism coupler. The demonstration was made on a glass substrate. The throughput intensity is monitored by a vidicon camera. Since the poly-

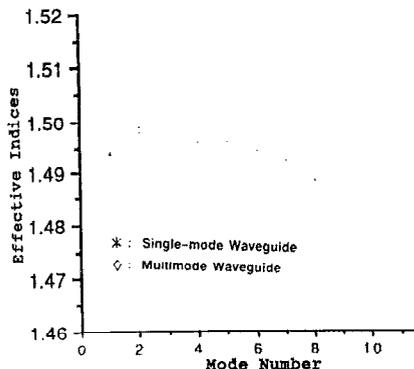


FIG. 3. Measured effective indices of two collinear waveguides.

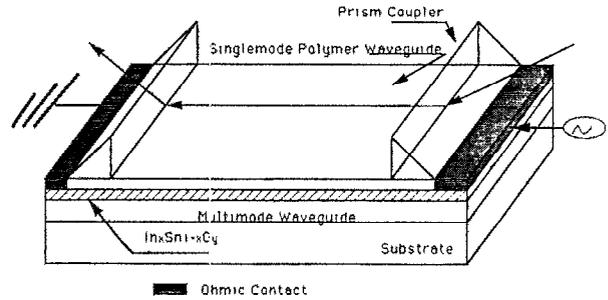


FIG. 4. Device structure of the polymer waveguide modulator.

mer waveguide can be constructed on any smooth surface, the multilayer structure can be implemented on any material of interest. The variation of the circular polarized throughput intensity of the single-mode guide as a function of the applied current is shown in Fig. 5. Sine-square type power transfer was observed along the waveguide propagating direction. 36 dB modulation depth, which combines 3 dB absorption loss and 33 dB phase-matched cross coupling, was observed with current density of  $\sim 1.8 \mu\text{A}/\mu\text{m}^2$ . The difference of the extinction ratio between TE and TM modes was within 0.1 dB. Note that the relatively long interaction length is primarily due to the relatively large value of  $\Delta n$  [Eq. (4)]. Theoretically, an interaction length  $L$  similar to that of the multiquantum well (MQW) device is achievable by optimizing the value of  $\Delta n$ .

As far as the modulation speed is concerned, the electrode structure we developed is similar to that of the traveling-wave structure. Therefore, the modulation bandwidth shall be<sup>9</sup>

$$\Delta f = 2V_c V_o / \pi (V_o - V_c) L \quad (5)$$

when 50  $\Omega$  impedance-matched structure (not shown) is employed.<sup>8</sup> In Eq. 5,  $V_c$  and  $V_o$  are the group velocities of the injected current and the optical wave, respectively. Equation (5) is valid if the recombination time of the minority carriers and the other time-dependent modulation mechanism are faster than the switching speed. In our present demonstration, both dc and ac (10 kHz) signals were employed to modulate the throughput intensity. Based on Eq. (5) multi Gbit/s modulation speed is theoretically achievable. Further results will be reported in the future publication.

The polymer waveguide material and the  $\text{In}_{1-x}\text{Sn}_x\text{O}_y$  film show an excellent transparent bandwidth from 300 to 2800 nm over which a series of useful wavelengths for optical communication is located. As a result, a large number of applications can be realized using the proposed architecture. Furthermore, the polymer waveguide material has proven capable of forming a high quality waveguide on any smooth surface, including semiconductor, conductor, and insulator, regardless of its conductivity and index of refraction. Local area network, CATV, optical sensor, optical signal processing, and computing, and coherent communication are some of the most useful areas where the polymer collinear modulator can be an attractive

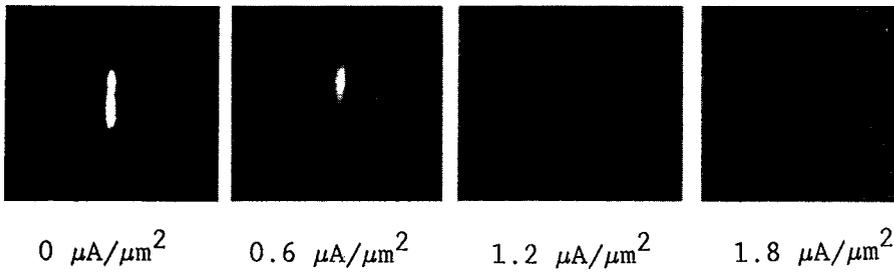


FIG. 5. Intensity modulation under different current injection densities (mode-dot Has  $\sim 40 \mu\text{m}$  in length).

device. Index modulation, due to current injection, is independent of the polarization of guided wave. As a result, the waveguide modulator was observed to be insensitive to the polarization of the guided wave. Absorption loss due to the  $\text{In}_{1-x}\text{Sn}_x\text{O}_y$  film was also confirmed. Such modulation effect is insignificant when compared with the phase-matched coupling.

In summary, we report herein the first single-mode collinear polymer waveguide modulator which is suitable to be implemented on any smooth surface including conductor, semiconductor, and insulator. The highly asymmetrical structure provides an easy means to phase match the guided mode between the single-mode waveguide and a highly multimode waveguide. The conventional directional coupler needs to fabricate the waveguide pair with almost equal parameters to fulfill the optical power transfer from one guide to the other. The new multilayer structure we developed here allows us to have a large dynamic range of the effective index of the single-mode waveguide. Thereby, the criterion for device fabrication is simple to achieve. Thirty-six dB modulation depth was achieved with an injected current density  $\sim 1.8 \mu\text{A}/\mu\text{m}^2$ .

Finally, the polymer material and the  $\text{In}_x\text{Sn}_{1-x}\text{O}_y$

have a transparent bandwidth from 300 to 2800 nm which covers almost all the major wavelengths for optical communication and signal processing. Consequently, further applications of the demonstrated device in various related areas are very attractive.

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