Electro-optic and all-optical phase modulator on an indium tin oxide single-mode waveguide

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We have successfully demonstrated an In_2O_3:Sn semiconductor thin-film waveguide. The energy gap of the film can be manipulated from 3.1 eV (0.4 μm) to 3.7 eV (0.335 μm) by changing the ratio of In_2O_3 and SnO_2. Waveguide propagation losses of 3 dB/cm for transverse magnetic (TM) and 8 dB/cm for transverse electric (TE) guided waves were experimentally confirmed at the wavelength of 632.8 nm. A phase modulator containing an indium tin oxide waveguide, two holographic mirrors, two microprisms, and two ohmic contacts were fabricated. Electro-optic (current injection) and all-optical modulations were conducted. A modulation depth of 18% was experimentally confirmed for the current injection device, using 15-V applied voltage, and a modulation depth of 15% using 250 mW 355 nm UV light as the activation sources. An In_2O_3:Sn waveguide device working at the cutoff boundary was made. A modulation depth of 26 dB was measured with an applied voltage of 30 V. An array of applications, including use in current sensors, ozone UV sensors, attenuated total reflection (ATR) modulators, delay lines for phased array antennae, and multiquantum wells are highly feasible.

We report the development of a new In_2O_3 film for use as an optical waveguide and an electro-optic (current-injection) and all-optic modulator. The In_2O_3:Sn film has good transparency which allows a large number of optical wavelengths to be multiplexed with the carrier signal. The index of refraction of the In_2O_3:Sn film shifts from 2.0 with 100% In_2O_3 to 1.75 with 95% In_2O_3 and 5% SnO_2 at the 632.8 nm wavelength. Furthermore, the In_2O_3:Sn is a semiconductor film, so the effective index of the guided mode can be modulated by current injection.[1,2] With an electric field or an optical beam as the origin of the current injection, electro-optic (current injection), and all-optic modulators, respectively, can be made with the proposed thin film.

Transparent, electrically conducting In_2O_3 films are widely used in solar energy conversion, in optoelectronics, and in other branches of technology. The wide transparent bandwidth of In_2O_3 films makes it a good candidate as a waveguide material. By varying the ratio of In_2O_3 and SnO_2, the index of refraction and the band gap of the In_2O_3:Sn can be manipulated over a wide range of interest. The index of refraction of an indium tin oxide film can be represented by

$$n^2 = \varepsilon_{\rm opt} - \frac{4\pi N e^2}{m^* \omega_0^2} \quad (1)$$

where $\varepsilon_{\rm opt}$ is the high-frequency permittivity, m^* is the effective mass of the electron, N is the carrier density, and ω_0 is the frequency of electromagnetic oscillations at which measurements were carried out ($\omega_0 = 2\pi c/\lambda$). The decrease in the index of refraction (Fig. 1) with the decrease in the In_2O_3 mole percentage implies that the carrier concentration is increased as more SnO_2 is doped into the In_2O_3 film. The experimental values of the energy band gap were obtained by detecting the absorption edge.

The band gap varies from 3.1 eV (0.4 μm) with pure In_2O_3 to ~3.7 eV (0.335 μm) with 5% SnO_2 in the In_2O_3 film.[3] For all-optical modulation, the band-gap energy E_g is an important parameter in determining the wavelength of optical activation. To date, there are no reported data on the band structure of indium tin oxide film. The result for band-gap measurement is correct for both direct and indirect band gaps. In the case of indirect band-gap absorption, a phonon must be absorbed to supply the missing crystal momentum. This is typically a few hundredths of an electron volt and therefore of little consequence except in semiconductors with a very small energy gap.[4]

A variety of In_2O_3:Sn guided wave devices working in the single-mode regime was investigated. Formation of a single-mode waveguide was first confirmed by using prism coupling methods. With a 98%, 300 nm In_2O_3:Sn film, a single-mode TM (transverse magnetic) waveguide was experimentally confirmed. The result of the demonstration is displayed in Fig. 2 where a bright streak is apparent in the photograph. The measured effective index was 1.750. Note that the smoothness of the glass substrate plays an important role for the realization of such a waveguide. To further characterize the waveguide propagation loss, loss measure-

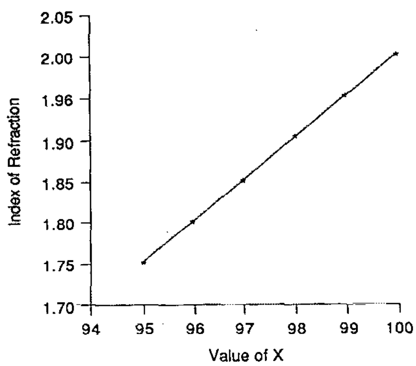

FIG. 1. Index of refraction of In_2O_3:Sn film at 632.8 nm wavelength. X represents the mole percentage of In_2O_3.

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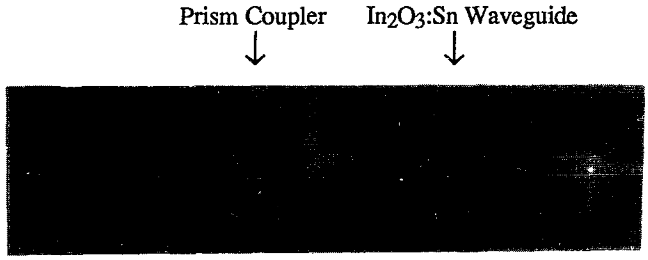

FIG. 2. Single-mode In_2O_3:Sn waveguide on glass substrate (the total length of the waveguide is 5 cm).

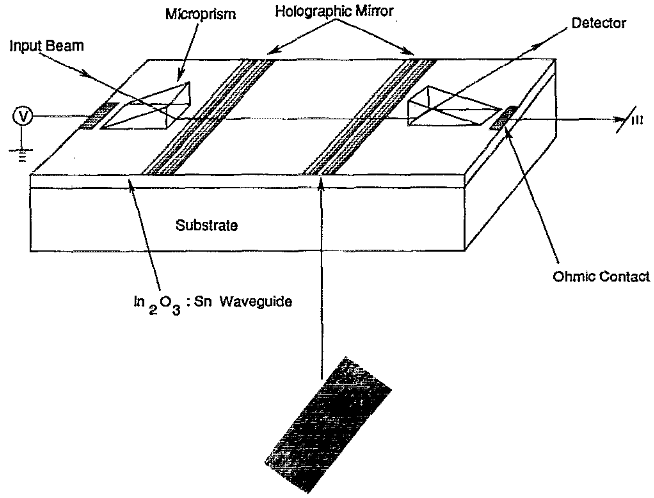

FIG. 3. Device structure for an In_2O_3:Sn waveguide modulator.

ment was conducted using a two-prism method. Both TE and TM modes were measured. The waveguide propagation losses of 3 and 8 dB/cm were experimentally confirmed for TM and TE, respectively. The measured results implied that a TM guided wave is more suitable than a TE guided wave for making a modulator with high modulation depth.

The electro-optic and all-optic modulation of the indium tin oxide film was carried out by manipulating the carrier concentration of the In_2O_3:Sn. There are two methods to provide this manipulation. The first method is to electrically inject a time-varying current and the second is to optically activate the device using a short wavelength light source with photon energy larger than the band-gap energy E_g. For either case, the carrier concentration of the indium tin oxide film will be perturbed and an index modulation within the film will be generated accordingly.

The device structure we employed is a Fabry–Perot waveguide resonator. The reflection mirrors are constructed using a holographic phase grating (HPG). The existence of the waveguide propagation loss and less than 100% reflectivity of the HPG reduce the peak transmission to less than unity. The structure of the basic device fabricated is shown in Fig. 3. The index modulation within the cavity can be generated either by current injection or by optical activation.

An indium tin oxide waveguide modulator using the current injection method was demonstrated first. The current injection was realized by applying an ac voltage across the two ohmic contacts shown in Fig. 3. A modulation depth of 18% is observed (not shown) at an ac pulse signal of 60 kHz and an amplitude of 15 V.

The measured index modulation due to current injection was on the order of 10^{-3}. Note that the modulation depth is limited by (1) the waveguide propagation loss which is 3 dB/cm for TM mode and (2) the reflectivity of the holographic mirror which is $\sim 30\%$ in our experiment. A modulation depth close to 100% can be realized by minimizing the waveguide propagation loss and by enhancing the reflectivity of the holographic mirrors. A further current induced modulation was demonstrated by injecting an electrical current into the indium tin oxide film through the ohmic contact. The In_2O_3:Sn waveguide has a waveguide effective index very close to cutoff ($n_{eff} = 1.525$). Unlike the linear electro-optic effect where the index modulation is electric-field orientation dependent, the current induced index modulation reduces the index modulation regardless of the direction of current injection. Consequently, the cutoff modulation can be realized by injecting a current into a single mode In_2O_3:Sn waveguide having an effective index close to the cutoff boundary. The voltage needed to achieve the cutoff modulation is[5]

$$V = \frac{(n_{eff} - n_s)\, R}{k} \tag{2}$$

where k is a constant representing the response of the refractive index of the film, R is the resistance of the film, and n_s is the substrate index of the waveguide. Figure 4 shows the experimental throughput of an acousto-optically modulated HeNe signal (85 MHz) under a dc voltage of 0, 20, and 30 V applied to the ohmic contact associated with the device (Fig. 3). An extinction ratio of 26 dB was experimentally confirmed in this case. From the results shown in Fig. 4, one can conclude that indium tin oxide film can be used as a power limiter.

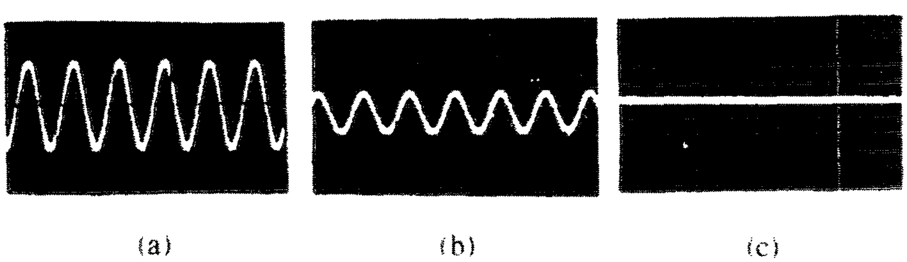

FIG. 4. Throughput intensity modulation of acousto-optically modulated HeNe light (85 MHz) using dc power of (a) 0, (b), 20, and (c) 30 V.

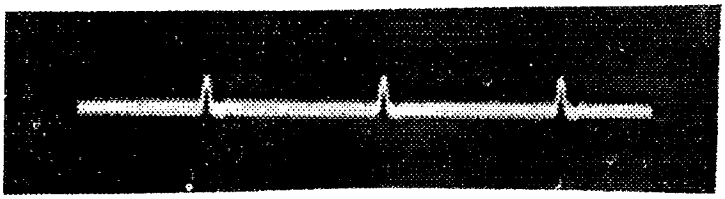

FIG. 5. 4 kHz modulated signal of 632.8 nm HeNe guided wave using 355 nm UV laser as the activation source. Modulation depth of 15% is observed.

An alternative to activating the In_2O_3:Sn waveguide modulator is to generate a time-dependent carrier density through electron-hole pair generation. The band-gap energy varies from 3.1 to 3.7 eV (Ref. 3) which corresponds to an optical wavelength between 0.4 and 0.335 μm. To investigate the possibility of absorption due to shallow- and deep-level states,[6] an argon laser working at 436 nm was first employed for the demonstration. The experimental setup is shown in Ref. 3. HeNe 632.8 nm light is prism coupled into the indium tin oxide planar waveguide. The 436 nm is focused into the active region between the two holographic mirrors (Fig. 3). The waveguide device used for this demonstration is the same as that of the current-induced modulator. A 436 nm light with intensity as high as 5 W/mm^2 was shone on the active region. Experimentally, no intensity modulation was observed under this condition. This result implies that the absorption due to deep and shallow levels is negligible. For our experimental scheme, index modulations as small as 10^{-6} allow us to clearly observe the phenomenon. By shifting the activation light source from 436 to 355 nm (third harmonic of the YAG laser), an all-optical experiment was conducted. 50 mW, 355 nm UV light was generated from the BBO crystal. By collimating and imaging the UV light onto the active region through UV lenses, electron-hole pairs can be generated from the indium tin oxide film (98% In_2O_3). A YAG laser, a third harmonics generator (BBO cavity), a UV beam chopper, a HeNe laser, prism couplers, an In_2O_3:Sn waveguide modulator, a Si detector and electronic equipment for amplification and detection were employed for this demonstration. The setup can be found in Ref. 7. The purpose of the beam chopper is to modulate the UV light so that a time-dependent carrier concentration can be created within the indium tin oxide film. The throughput light or HeNe guided wave is imaged onto a *p-i-n* silicon detector which is connected to an amplifier. The outcome of the detected signal is displayed in Fig. 5. A 4 kHz modulated guided wave which is synchronized with the electrically chopped UV light at 632.8 nm is present. The modulation depth of the signal was measured to be ~15%. The modulation speed is limited by the chopper frequency which has a maximum of 4 kHz.

An indium tin oxide waveguide modulator is introduced for the first time. Implementation of either current or UV optical activation source on the device is a straightforward method to realize such a device. Manipulation of the band gap by changing the ratio of In_2O_3 and SnO_2 is a promising approach for microstructure optoelectronic devices. An array of applications are feasible based on the present technology. These include current sensors, ozone UV sensors, phase resonant attenuated total reflection (ATR) modulators, power limiters, phased array antennae, and multiquantum well (MQW) devices. A detailed description of each individual application can be found in Ref. 7.

The feasibility of engineering the band gap by altering the concentration ratio of In_2O_3 and SnO_2 provides us with a far-reaching application scenario—MQW. It is clear that both nonlinear all-optical devices such as optical bistable devices[8] and the electroabsorption devices such as self-electro-optic effect devices (SEED)[9] are very attractive.

We have successfully demonstrated a single-mode indium tin oxide waveguide for both TE and TM modes. The band gap and thus the activation photon energy can be tuned from 3.1 eV (0.4 μm) to 3.7 eV (0.335 μm) by changing the ratio of In_2O_3 and SnO_2. Phase modulation using an In_2O_3:Sn single-mode waveguide in conjunction with two holographic mirrors was demonstrated in both a current injection scheme and an optical activation scheme. The 18% modulation depth for current injection modulation at a pulse frequency of 60 kHz and all-optical modulation with 15% modulation depth using 355 nm light (third harmonic of the YAG laser) were experimentally confirmed. The relatively low modulation depth was attributed to the low reflectivity of the holographic mirrors and 3 dB waveguide propagation loss. A further experiment on an indium tin oxide waveguide modulator working in the cutoff regime was conducted by injecting a dc current into the waveguide through the associated ohmic contact. Modulation depths as high as 26 dB were measured. Due to the simplicity and innovativeness of the proposed concept, a number of highly feasible applications were presented.

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