Polymeric electro-optic modulator based on 1×2 Y-fed directional coupler

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We have demonstrated a polymeric electro-optic modulator based on a 1×2 Y-fed directional waveguide coupler. The symmetric geometry of the 1×2 Y-fed directional coupler provided the modulator unique characteristics of intrinsic 3 dB operating point and two complementary output ends. A low switching voltage of 3.6 V and a high extinction ratio of 26 dB were obtained with the modulator operating at a wavelength of 1.34 μm. The modulator was fabricated with a novel electro-optic polymer that was synthesized from polyurethane cross-linking with a chromophore.
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External electro-optic (EO) modulators have important applications in optical communication, phase array antennas, and sensing systems.[1,2] Although inorganic crystal (such as $LiNbO_3$) based modulators are commercially available now, further applications of such modulators in high-speed fields are restricted due to the large phase velocity mismatching between the guided optical wave and the modulating microwave signal.[3,4] In comparison to the expensive crystals and their complicated fabrication processes, electro-optic polymers have many intrinsic advantages, such as their higher electro-optic coefficients, less phase velocity mismatching, and flexibility of device fabrication. EO polymer-based Mach-Zehnder modulators have been demonstrated recently by several groups.[5–8] In a Mach-Zehnder modulator, the input light is split into two parallel waveguide arms and combined together through two Y-branches respectively. Usually the separation of the two waveguides is large enough to eliminate the coupling between the two channels. To ensure a linear modulation, a direct-current (dc) bias is required to set the modulator at the half-power point, which results in more complicated circuit fabrications and serious linearity distortion due to the dc drift phenomena.[9,10] Therefore, it is worthwhile to investigate other type of modulators to overcome these problems.

Thaniyavarn first reported a 1×2 Y-fed directional coupler modulator using inorganic crystal material ($Ti:LiNO_3$).[11] The high linearity, low intermodulation distortion, and other unique characteristics of such kind of modulators were investigated theoretically as well.[12] Based on a host-guest EO polymer system and poled with a domaininversion technique, we recently demonstrated a 1×2 coupler modulator with a switching voltage of 24 V.[13] Apparently, it is necessary to reduce the switching voltage further and improve the operation stability of the modulator for the potential application in the future. In this letter, we present a 1×2 Y-fed directional waveguide coupler modulator fabricated with a novel EO polymer system. Due to the higher EO coefficient and better stability of the new EO polymer, the switching voltage is reduced to 3.4 from 24 V, while the extinction ratio is increased to 26 from 23 dB over the previous publication.[13]

Basically, a 1×2 Y-fed waveguide modulator consists of a single-mode Y-junction splitter and a codirectional coupler with two parallel and symmetric waveguide channels. The schematic diagram and its fabrication parameters of the modulator are shown in Fig. 1. Light is fed in and split into the two symmetric waveguides equally through the Y-junction region. The codirectional coupler guides the two single-mode light beams traveling along the two channels. With no modulating voltage applied, the modulator is set to the 3 dB operating point automatically due to the symmetric structure of 1×2 Y-fed directional coupler. While a driving voltage is applied through the electrodes over the coupler region, however, light can be coupled from one channel into the other. The 1×2 Y-fed coupler modulator has two complimentary optical outputs. Usually a 1×2 Y-fed coupler modulator is characterized by its interaction length (L), its coupling conversion length (l_c), and the mismatch $\Delta\beta$ of propagation constants between the two channels. For a push-pull structure, the mismatch $\Delta\beta$ caused by the driving voltage is determined by

$$\Delta\beta = \frac{2\pi}{\lambda} n_e^3 r_{33} \alpha \frac{V}{d}, \tag{1}$$

where λ is the optical wavelength, n_e is the extraordinary index of EO film, d is the electrode spacing, and α is the overlap integral between the applied electrical field and the optical field ($0<\alpha<1$). Using the coupled-mode theory,[14]

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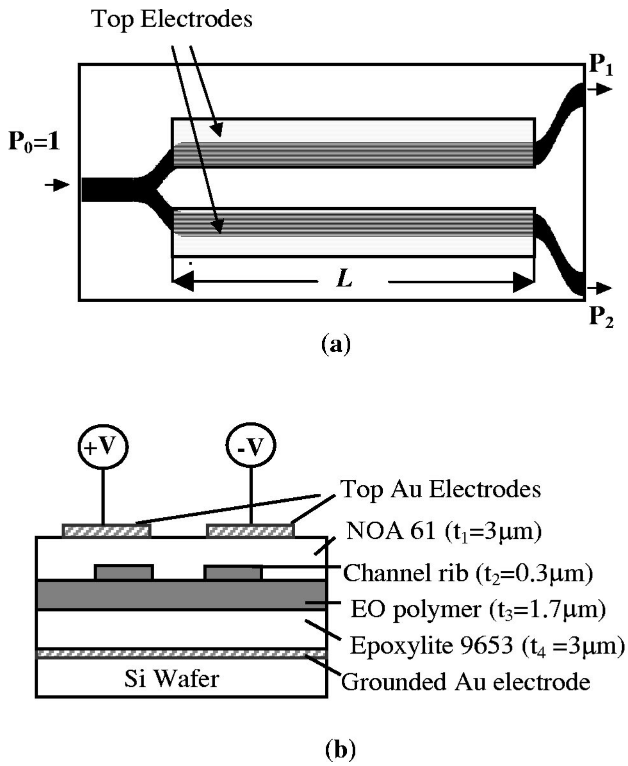

FIG. 1. Schematic diagram and fabrication parameters of the 1×2 Y-fed coupler modulator. (a) Top view. (b) Cross section. The channel width was 4 μm. The separation between the two channels was 6 μm.

an expression of the light power outputting of the modulator can be obtained. In a normalized condition, the light power P_1 of the upper branch is given by

$$P_1=\frac{1}{2}\left[1-\frac{2xy}{r^2}\sin^2\left(\frac{\pi r}{2}\right)\right], \tag{2}$$

where

$$x=\Delta\beta L/\pi=\frac{2n_e^3 r_{33}\alpha L}{\lambda d}V\propto V,$$

the normalized driving voltage; $y=L/l_c$, the normalized interaction length; and $r^2=x^2+y^2$.

From the condition of power conservation, the power in the lower branch is $P_2=1-P_1$. It is clear that x is a linear function of the driving voltage, although the normalized interaction length y is independent to it. According to Eq. (2), the 1×2 Y-fed coupler modulator is set at the 3 dB operation point automatically, i.e., $P_1=P_2=1/2$ when no driving voltage is applied. Figure 2 shows the simulated results of the light intensity versus driving voltage with $y=0.3$, $1/\sqrt{2}$, 1.0, and $3/\sqrt{2}$, respectively. Notice that maximum modulation depths are different with different values of interaction length. A 100% depth is reached when $y=1/\sqrt{2}$ and $3/\sqrt{2}$. Theoretically, the 100% modulation depth is possible only when $y=L/l_c=(2n+1)/\sqrt{2}$ ($n=0,1,2...$), according to Eq. (2).

The EO polymer we used was a thermosetting polyurethane system cross-linking with a novel chromophore (FTC) that was synthesized from 5-[4(N, N-dialkylamino) phenyl] vinylthiophene-2-carbaldehydes (the donor-bridge) and 2-dicyanomethylen-3-cyano-4,5,5-trimethyl-2,5-dihydrofuran (the acceptor).[15,16] Polyurethane was used to

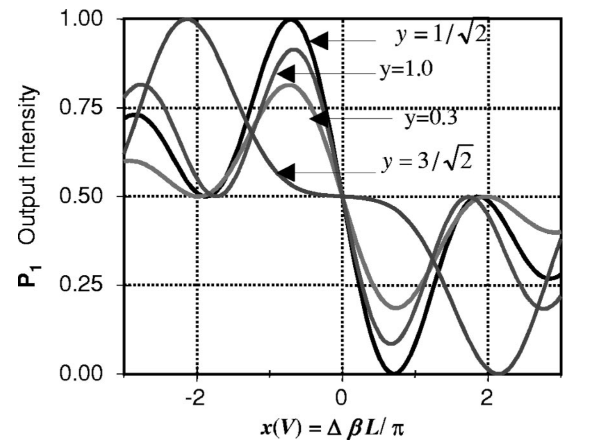

FIG. 2. Simulated results of light modulation vs driving voltage. The horizontal axis is the normalized driving voltage, and the vertical axis is the light intensity output of one branch of the modulator. When $y=1/\sqrt{2}$ and $y=3/\sqrt{2}$; the 100% depth of modulation is reached.

enhance the polymer stability to thermal environment.[7] Detailed information concerning the synthesis and the poling process of this material system will be reported elsewhere. To fabricate the EO polymer film, a prepolymer was synthesized first with the FTC chromophore and the monomers of polyurethane. The prepolymer and crosslinker triethanolamine were dissolved in dioxane and spin coated on silicon wafer with a ground electrode for poling and a layer of bottom cladding. The thickness of the EO polymer film was controlled at 2 μm by adjusting the spin-coating speed. After drying in a nitrogen-purged oven at room temperature, the EO film was poled for about one hour at 100 °C with a corona poling method[7] and cooled down to the room temperature while keeping the poling voltage on. The thermosetting cross-link of the material system occurred simultaneously during the poling process. The polymer EO coefficient was 25 pm/V, measured with an attenuated total reflection (ATR) technique.

The cross-section of the modulator is shown in Fig. 1(b). A silicon wafer was chosen as the substrate. A 2000-Å-thick Au film was deposited by electron beam method for the ground electrode. A 3-μm-thick layer of polymer, Epoxylite 9653-2 (n=1.54@1.31 μm), was used as the bottom cladding. The EO polymer film was spin coated and poled as explained above. The waveguide channels were fabricated with oxygen plasma etching (RIE) technique. The RIE processing parameters, such as the plasma pressure, radio-frequency (rf) power, oxygen flowing flex, and etching time, were optimized experimentally to make an excellent optical waveguide. The etched waveguide rib was 0.3 μm in depth and 4 μm wide with a channel separation of 6 μm. A layer of 3-μm-thick ultraviolet (UV)-curable polymer (NOA61, Norland Products Inc., n=1.54@1.31μm) was spin coated as the top cladding. Two top electrodes were patterned with normal lithography and wet etching technique. At last, the sample was diced, polished, and packaged for testing. In our experiment, the refractive index of the EO polymer was determined to be 1.62 (for TM) at the wavelength of 1.3 μm. The coupling length of the directional coupler was 1.8 cm. The top electrode length was 1.3 cm, corresponding to the minimum value of $L/l_c=1/\sqrt{2}\approx 0.707$ to fabricate a modula-

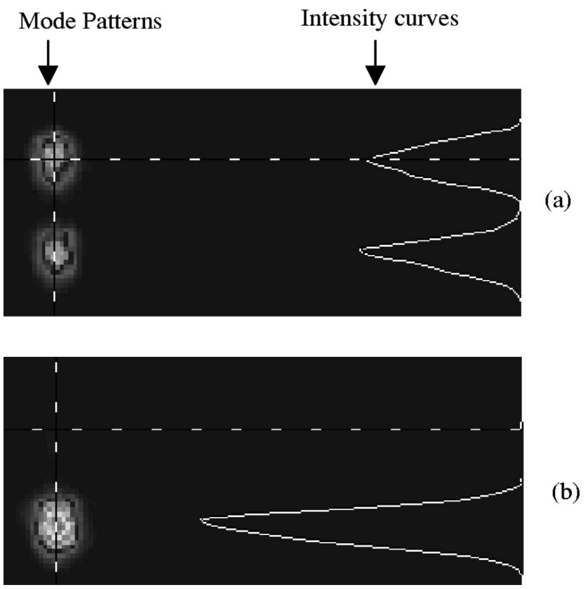

FIG. 3. Mode profiles coupled out of the two branches of the modulator under different driving voltages. (a) $V=0$, (b) $V=1.8$ V

tor with a 100% modulation depth. Two symmetric S-bend branches were used to reduce the radiation loss within the Y-branch splitting region.

The modulator was tested using a diode-pumped Nd:YVO_4 laser at the wavelength of 1.34 μm. The laser beam, polarized in the TM direction, was coupled into the device and collected by two 60× objectives, respectively. The output light was measured with a photodetector. The mode profile was recorded with an IR camera (Electrophysics Model 7290). Two equal but opposite voltage signals were applied to the top electrodes, respectively. The bottom electrode was grounded. Figure 3 shows the mode patterns and the intensity profiles of the two light beams of the modulator measured under different driving voltages. When no voltage was applied, the two intensity profiles of the two branches were almost identical, as shown in Fig. 3(a), corresponding to an equal intensity splitting within 0.4% accuracy. Therefore, the modulator was intrinsically set at the 3 dB half-power point. While the driving voltage was increased to 1.8 V, the light in the upper branch of the modulator was coupled into the lower branch, where the light pattern of the upper branch disappeared and the intensity profile of the lower branch reached maximum [Fig. 3(b)]. It was confirmed that the switching voltage[11] applied to modulate the light of either branch from a bar state (maximum intensity) to a cross state (minimum intensity) was 3.6 V, corresponding to a light extinction ratio of 26 dB. The alternating-current (ac) modulation responses of the two branches versus driving voltage are further presented in Fig. 4. The triangle curves in the figures were the driving voltage signals at the frequency of 50 kHz. Notice that the light intensities out of the two branches were complementary, i.e., $P_2=1-P_1$.

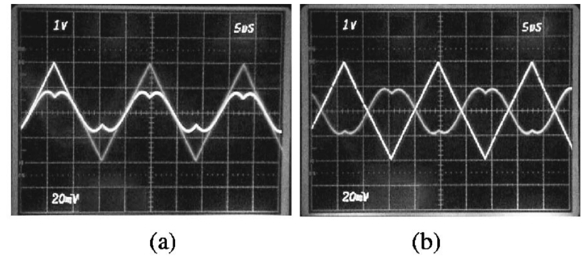

FIG. 4. Modulation curves displayed on an oscilloscope. (a) the top branch of Fig. 1, (b) the bottom branch.

With a laser input of 35 mW ($\sim 3\times 10^5$ W/cm^2), the modulator had been operating for more than 500 h over the past seven months, within which the same experimental result has been routinely observed without any drifting.

In conclusion, we have successfully demonstrated a polymeric modulator based on the structure of 1×2 Y-fed waveguide codirectional coupler. The modulator was fabricated with a novel EO polymer with an EO coefficient of 25 pm/V. A very low switching voltage of 3.6 V and a high extinction ratio of 26 dB were achieved with the modulator operating at a wavelength of 1.34 μm. The unique modulation characteristics of the 1×2 Y-fed coupler modulator were discussed as well.

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