20 GHz electro-optic polymer Mach–Zehnder modulator

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An electro-optic (EO) polymer-based integrated optic Mach–Zehnder modulator with a measured frequency response up to 20 GHz is reported. The device was fabricated with an EO polymer supplied by Akzo Research, bv, and utilized 50 Ω microstrip drive electrodes. A half-wave voltage of $V_\pi = 9$ V and a modulation depth of 90% were measured at 2 kHz. Modulation was observed out to 8.0 GHz using direct detection and out to 20 GHz using a frequency mixing technique, limited by the drive and receiver electronics.

Glassy polymer, nonlinear optical materials have been intensely investigated due to their potentially large electro-optic (EO) coefficients, low dielectric constants, and small dispersion from dc to optical frequencies.[1] Equally as important, organic polymers offer advantages over standard inorganic EO materials, such as $LiNbO_3$ and GaAs, in that multilayer integrated optical circuits can be fabricated on top of electronic substrates using processes and equipment that are largely in place for manufacturing integrated circuits (ICs).[2] The techniques used to form active waveguide channels, such as photobleaching,[3,4] electric field poling,[5,6] or micromachining,[7] are natural extensions of existing processes. Recent results indicate that electro-optic polymers can potentially be formulated with sufficient thermal stability for use in standard electronic fabrication, assembly, and packaging processes.[8] These materials may therefore provide a new class of highly integrated optoelectronic systems for very high-speed optical signal processing and interconnection.

This letter reports advances in the application of organic EO polymer materials to very high-speed integrated optic modulation. A serious limitation of current $LiNbO_3$ modulators is the velocity mismatch between the electrical wave traveling down the drive electrode and the optical wave traveling down the optical waveguide. The high-speed modulation limit of the material can be estimated by the bandwidth-length product f_cL, giving the maximum modulation frequency f_c for a device of length L. For $LiNbO_3$ $f_cL \approx 9.6$ GHz cm for a standard Mach–Zehnder configuration,[9] while for organic poled polymer films $f_cL \approx 150$ GHz cm. The limiting factor for the poled polymer films will probably be rf loss in the electrodes, which increases as the square root of the drive frequency. In order to investigate the high-frequency electro-optic properties of poled polymer films, a Mach–Zehnder modulator was fabricated. This device had the special feature that each arm of the Mach–Zehnder could be modulated independently with a separate electrode, allowing frequency mixing response measurements. Using this "two-tone" modulation technique the device was driven at 20 GHz, which is the highest modulation frequency yet reported in an organic EO polymer-based device.

A diagram of the modulator layout and a cross section of the waveguide and impedance matched 50 Ω microstrip drive electrode is shown in Fig. 1. A standard Y-branch architecture with a 1° total branch angle was used. The device was fabricated using conventional IC manufacturing equipment. Three polymer layers were deposited as shown in Fig. 1: a hard acrylate cladding layer, followed by an EO polymer, then another cladding layer. The EO material consisted of a side chain polymer with a (dimethylamino)nitrostilbene, "DANS", nonlinear optical moiety with a glass transition temperature of $T_g = 140$ °C,[10] which was supplied by Akzo Research, bv. The waveguides were photobleached using an IC mask aligner, and microstrip electrodes were formed by gold plating. The active polymer layer was poled through the cladding at 70 V/μm for 1 min on top of a 120 °C hot plate. The completed wafer was diced, and the polymer end faces were prepared by cleaving. Completed devices were mounted as shown in Fig. 1. To minimize impedance mismatches, bonding pads were not used at the ends of the microstrip electrodes. A Wiltron K connector, with 0.15-mm-wide K-to-microstrip launcher, was positioned directly over the end of each microstrip electrode by pressure contact. The total end-to-end dc resistance of each electrode was 3.3 Ω. The electrical properties of the microstrip traveling wave electrodes were determined using an HP8510 network analyzer, and at 11

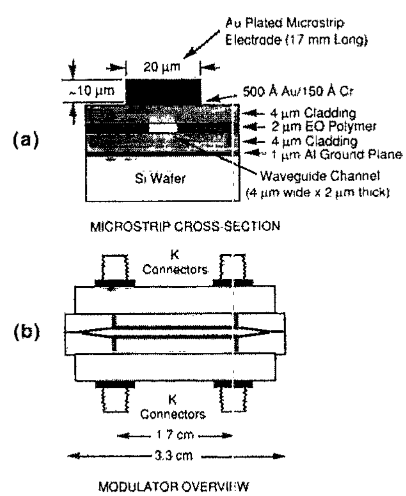

FIG. 1. (a) Cross section of the photobleached EO polymer optical waveguide and microstrip drive electrode from one arm of the Mach–Zehnder device, and (b) overview of the high-speed Y-branch Mach–Zehnder integrated optic modulator.

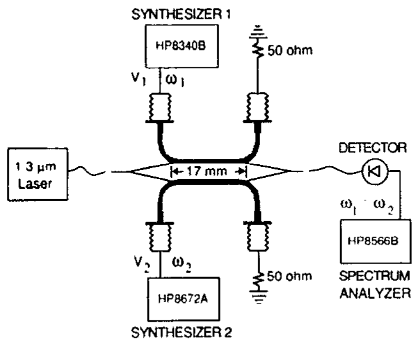

FIG. 2. Schematic showing dual-electrode measurement technique for Mach–Zehnder modulator fabricated with an EO polymer. Synthesizers 1 and 2, at different frequencies (ω_1 and ω_2), produce an optical signal at the difference frequency ($\omega_1 - \omega_2$) which is observed on the spectrum analyzer.

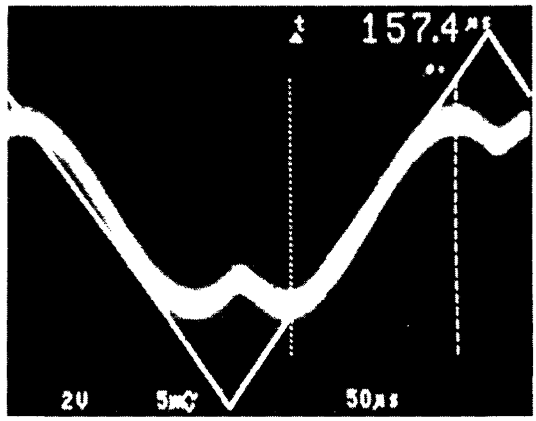

FIG. 3. Response of EO polymer-based Mach–Zehnder modulator to triangular waveform, demonstrating a half-wave voltage of $V_\pi = 9$ V.

GHz the measured impedance was 45.9 $\Omega + i3.6\ \Omega$, close to the design value of 50 Ω, and the electrical response was down only -6.7 dB.

A schematic diagram of the two-tone frequency modulation experiment is shown in Fig. 2. Related techniques have been used by others[11,12] to evaluate Mach–Zehnder devices. Expanding the output intensity of the Mach–Zehnder into frequency components with Bessel function amplitudes, and selecting the component of the output intensity at the difference frequency ($\omega_1 - \omega_2$) gives

$$I_{(\omega_1-\omega_2)} = I_0 J_1\left[\frac{\pi V_1}{V_\pi(\omega_1)}\right] J_1\left[\frac{\pi V_2}{V_\pi(\omega_2)}\right] [\cos(\omega_1-\omega_2)t] \times (\cos\phi_b). \tag{1}$$

Each arm is driven by applied voltage amplitude V_i at frequency $\omega_i (i = 1,2)$, ϕ_b is the dc phase bias, $V_\pi(\omega_i)$ is the half-wave voltage at ω_i, $J_1[x]$ is a first-order Bessel function, and I_0 is the input intensity. Equation (1) shows that an intensity modulation at the difference frequency results from phase modulation of each arm of the modulator at the high-frequency fundamentals.

The electro-optic modulation of the device was tested at both low and high frequencies, using a 1.3 μm DFB diode laser (Mitsubishi FU-45SDF-4). SELFOC lenses were used to end-fire couple light from the input polarization-maintaining optical fiber into the modulator and from the modulator into the output optical fiber pigtailed to a detector. Both the laser and detector were carefully shielded from electromagnetic pickup. To verify that the signal did not result from direct laser modulation by stray rf fields, the modulator was optically bypassed with fiber optic cable going directly to the detector, and no signal was observed. In addition, by driving one or both electrodes to higher power levels the output signal showed maximum and minimum values similar to those predicted by Eq. (1).

Shown in Fig. 3 is a measurement of the half-wave voltage of the device. A 2 kHz 14 V sawtooth wave was applied to only one device electrode over one arm of the Mach–Zehnder, and the optical output was directed to the detector and observed on an oscilloscope. The voltage necessary to turn the device from fully on to fully off was measured to be $V_\pi = 9$ V, giving an $r_{33} = 18$ pm/V, close to that expected from measurements on the pure polymer with the poling voltage of 70 V/μm. Akzo has reported poling at >200 V/μm,[10] which should increase r_{33} by a factor of 3 and yield a half-wave voltage of 3 V. The modulation depth of the Mach–Zehnder device was measured in a similar manner. The contrast ratio between the on-state and the off-state is ten, giving an extinction ratio of 10 dB. In these measurements, however, a large 100 μm core output fiber was used to reduce alignment sensitivity. This is much larger than the 2 μm by 4 μm output waveguide, and stray light in the cladding is also collected. It is likely that the actual extinction ratio of the device is better than 10 dB.

The direct response of the Malch–Zehnder device was measured by driving one electrode from 5 Hz to 200 MHz with an HP3577A network analyzer, detecting the output with an Antel model ARX-GA Ge avalanche photodiode with a built-in preamplifier having a response from dc to 2 GHz. Only one arm of the device was modulated and direct detection at the modulating frequency was employed. The frequency response was flat over the measured range. Similarly the modulator's response was measured using an HP8510 network analyzer and an Optoelectronics PD-50 photodiode with an Avantek AGT8235 preamplifier, with an approximate passband from 2 to 8 GHz. A clear modulation response from 20 to 40 dB above the noise floor was observed over the entire 2–8 GHz bandwidth. The signal exhibited a roll-off of approximately 20 dB over the region from 2 to 8 GHz and vanished above 8 GHz, where the detector was nonresponsive. This roll-off was due to the combination of roll-offs in the detector, amplifier, cables, and electrodes.

In order to determine the response of the EO polymer at frequencies above the present detector bandwidth, a two-tone frequency modulation experiment was carried out, as described above and shown in Fig. 2. In this case both electrodes over the two arms of the Mach-Zehnder were used. One arm of the Mach–Zehnder was modulated at 20 GHz with an HP8340B frequency synthesizer, while

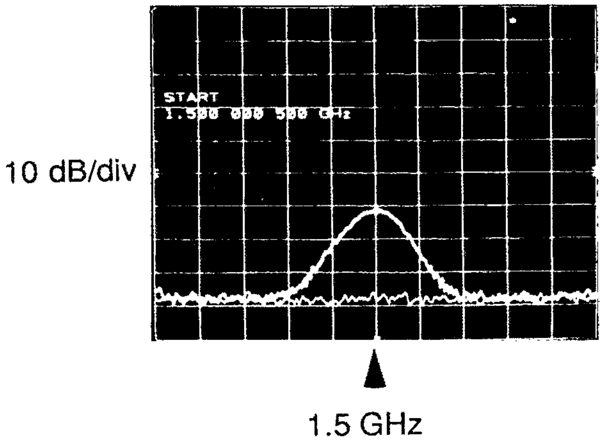

FIG. 4. Optical output signal at 1.5 GHz from electrode drive signals at 18.5 and 20 GHz, demonstrating device modulation at 20 GHz.

the second arm was modulated at 18.5 GHz with an HP8672A frequency synthesizer. The output signal at the difference frequency was then detected using the Antel model ARX-GA detector, and measured with an HP8560B spectrum analyzer. The output of the spectrum analyzer is given in Fig. 4, showing a clear signal 25 dB above the noise floor at the difference frequency of 1.5 GHz. The optical output intensity at the difference frequency was present only if each arm was modulated at its high frequency fundamental. The measurement was limited to 20 GHz by the available frequency synthesizers.

In conclusion, we have built and tested a multi-GHz Mach–Zehnder modulator based on an EO polymer. The modulator demonstrated a half-wave voltage of $V_\pi = 9$ V, an extinction ratio of 10 dB, and flat material and device response out to 200 MHz on a low-frequency testset. The device also showed clear modulation on a high-frequency testset out to 8.0 GHz using direct detection and out to 20 GHz using a frequency mixing technique, demonstrating that organic EO materials can be used for modulation in the multi-GHz regime. Improvements in the measurement instrumentation are now under way to allow higher frequency modulation and a meaningful comparison of organic EO materials with $LiNbO_3$ for high-speed modulation.

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