Push–pull electro-optic polymer modulators with low half-wave voltage and low loss at both 1310 and 1550 nm

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Push–pull polymeric electro-optic Mach–Zehnder (MZ) modulators with V_π of 1.2 and 1.8 V at 1310 and 1550 nm, respectively, with an interaction length of 2 cm are demonstrated. These devices were made from second-order nonlinear optic guest–host polymers that consisted of a phenyltetraene bridged high $\mu\beta$ chromophore guest and an amorphous polycarbonate host. Poling was done in N_2 atmosphere to avoid chromophore bleaching by oxidation. A MZ-like two-arm microstrip line was used as the driving electrode in these devices. The optical response dropped 3 dB electrical from 2 to 20 GHz. These 3 cm long devices have 5 dB total chip loss at both wavelengths and good thermal stability.
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Polymeric electro-optic (EO) modulators[1] are of great interest for wide band optical communication systems and optical signal processing because of their potentially large rf bandwidth and low switching voltage. An EO polymer modulator operating at over 100 GHz was demonstrated several years ago[2] and, more recently, a modulator with sub-1 V half-wave voltage at 1310 nm was reported.[3] However, to effectively compete with inorganic devices, the modulators must operate at 1550 nm and issues such as optical insertion loss and thermal stability must be addressed. In this letter, we report the fabrication and experimental results of push–pull polymeric Mach–Zehnder (MZ) modulators with low V_π, low loss, and good thermal stability at both 1310 and 1550 nm.

The EO polymer material used in this work has been described earlier and is based on the structural design of chromophores to reduce the large dipole–dipole interactions between chromophores and to thereby increase the EO coefficient.[3] The chromophore is a phenyltetraene bridged chromophore labeled CLD which is doped into an amorphous polycarbonate[4] (APC) polymer host. Two different CLD chromophores were used in our modulators, CLD-1 and CLD-75. The molecular structure of the CLD-1 chromophore is given in Ref. 3. CLD-75 has the same π-conjugate backbone as CLD-1 but has additional bulky side groups in the center of the chromophore to reduce intermolecular interactions. CLD-1 was used in a poly(methylmethacrylate) (PMMA) host to realize the sub-1 V modulator.[3] However the PMMA host has a relatively low T_g which results in modest thermal stability of the molecular alignment. The CLD-1/APC (30 wt. % density) films corona poled in air gave an EO coefficient of 90 pm/V at 1.06 μm.[5] By monitoring the optical second harmonic from the film as the temperature is increased (10 °C/min), the short term thermal stability of the molecular alignment was measured to be 120 °C.[5] The infrared loss in these materials is determined by the loss of the host polymer and the CLD-1/APC has measured a low loss window in both the 1300 and 1550 nm bands.[6]

In the push–pull design, which reduces the V_π by a factor of 2, the chromophores in the two arms of the Mach–Zehnder modulator are aligned in opposite directions by electrode poling. The same fabrication techniques used in Ref. 5 were used in the push–pull devices. Two μm thick Au was coated on a Si substrate. The UV-curable epoxies UV15 (from Masterbond Co.) and UFC-170[7] were used as the lower cladding and the upper cladding, respectively. The cladding layers and the core layer were each approximately 2.5 μm thick. The ridge waveguides were defined by reaction ion etching (RIE) in oxygen and the modulators were fabricated with various waveguide widths of 7, 6, 5, and 4 μm. The waveguide ridge height was chosen to be ~0.35 μm to assure single mode operation with all waveguide widths. The Au poling electrode pattern was made on top of UFC-170 layer and then covered by a 3 μm thick AZ5214 photoresist layer, which acted as a protection layer to prevent avalanche breakdown through air between the electrodes. The samples were prebaked on the poling stage at 130 °C for 10 min in N_2 atmosphere before poling. The poling was also done in N_2 atmosphere at a temperature of 140 °C and a voltage of 800 V (400 V for each arm). The poling current was monitored with a picoamperemeter and limited to 300

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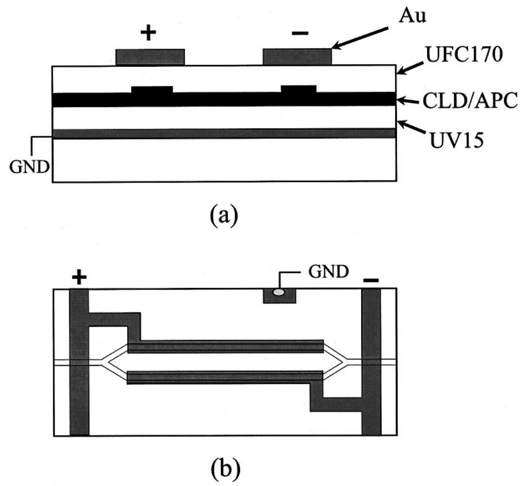

FIG. 1. (a) Cross section and (b) top view of the push–pull Mach–Zehnder modulator and the poling electrode.

nA. The device cross section and the poling electrodes are shown in Fig. 1. After poling, the poling electrodes were removed and a final driving microstrip lines were fabricated by using a Cr–Au seed layer and plated Au of $\sim$3 μm thickness. The end facet of the device was diced with a nickel blade. The final device was 3 cm long with an interaction length of 2 cm.

It is critical that the electrode poling be done in an inert atmosphere to prevent bleaching of the chromophores by free oxygen in the polymer. In poling experiments in air on straight waveguides, we found that the bleaching can reduce the index of refraction of the core material sufficiently to completely lose the lateral mode confinement. We also found that the bleaching required both a high temperature and electric field. Waveguides, in air, subjected to only heating or to only the applied electric field do not show increased loss. Figure 2 shows how poling in an inert atmosphere (N_2) significantly reduces the bleaching and therefore poling induced loss. The 2 cm long waveguides were poled at the same temperature of 140 °C for 20 min, but at different voltages of 400, 500, and 600 V and in different atmospheres. The optical transmission was measured before and after poling and the difference is the poling induced loss. Measurements were

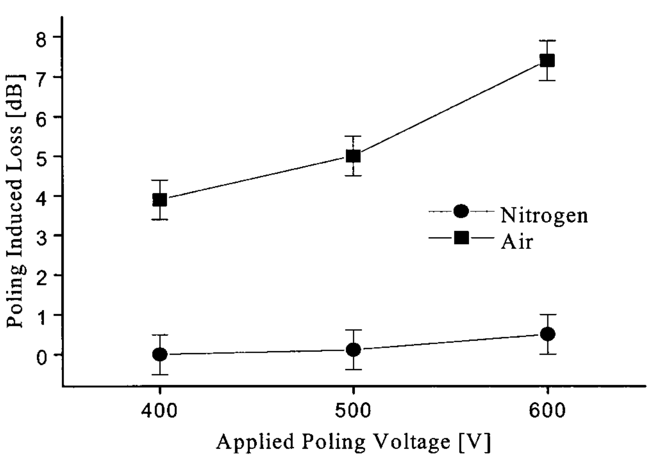

FIG. 2. Poling induced loss measured from straight waveguides of six different devices poled, respectively, in air and in N_2. The typical error of the loss measurement is $\pm$0.5 dB.

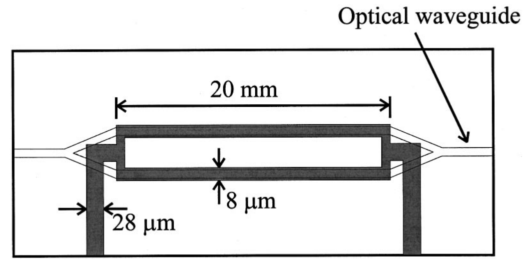

FIG. 3. Two-arm MZ-like microstrip transmission line.

made on several waveguides to average the variation in the coupling loss. When poled in air, the insertion loss of the device increased by 4–7 dB, corresponding to 2–3.5 dB/cm. In contrast, when poled in N_2, the poling induced loss was negligible. We also investigated the influence on the poling induced loss of the N_2 purging time before the poling by varying the purging time from 30 min to 24 h. The poling induced losses were almost the same for all the cases, which means that O_2 can be driven out of the films very quickly, especially at high temperatures.

In the push–pull poled interferometer, the two arms must be sufficiently separated laterally to prevent dielectric breakdown between the poling electrodes at high poling voltages. In our design the separation of the two arms was 50 μm from center to center. If a single microstrip line electrode of sufficient width to cover both arms were used, the characteristic impedance of the microstrip line would be too low. To provide higher impedance, the upper electrode is split into two electrodes as shown in Fig. 3.[8] The input characteristic impedance for the dimensions shown is approximately 35 Ω and the impedance of each arm is approximately 70 Ω.

The performance of the devices were measured by using a standard single mode input fiber and a 20× microscope objective output lens. At both 1310 and 1550 nm, the total insertion losses, from the fiber through the device to the detector, were measured to be 9–10 dB. This is similar to other modulators made from the same materials[5] and is consistent with an earlier cutback measurement of waveguide loss ($\sim$1.7 dB/cm). The chip loss (excluding the coupling loss) was estimated to be $\sim$5 dB. The low frequency optical response was measured by using a 1 kHz triangular electrical modulation signal. The V_π of CLD-75/APC devices was 1.2 V at 1310 nm and 1.8 V at 1550 nm, corresponding to a $V_\pi L$ product of 2.4 and 3.6 V cm, and that of the CLD-1/APC devices was 1.4 and 2.1 V at 1310 and 1550 nm, respectively, corresponding to a $V_\pi L$ product of 2.8 and 4.2 V cm. For the CLD-75 material this corresponds to an electro-optic coefficient of 47 pm/V at 1310 nm and 36 pm/V at 1550 nm. The extinction ratio of the modulator was larger than 20 dB, which indicates single mode operation and balanced poling of the two optical arms.

The high frequency response measurement of the unpackaged push–pull modulator is shown in Fig. 4 in which the optical response dropped 3 dB electrical, from 2 to 20 GHz. Since the impedance of our modulator is only 35 Ω, there is a strong parasitic response below 2 GHz due to the impedance mismatch between 35 and 50 Ω. This parasitic response is not intrinsic to the device and can be eliminated by proper on chip rf line termination. The response above 2

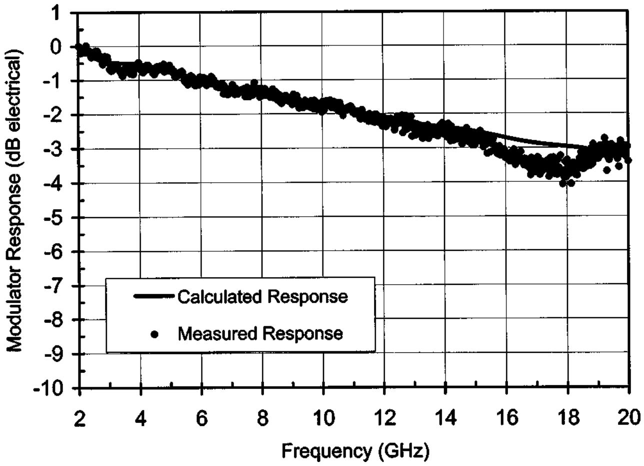

FIG. 4. Measured and calculated push–pull modulator optical response, electrical, from 2 to 20 GHz. The data are normalized to 2 GHz. The calculated response is based on the measured microstrip line loss.

GHz is consistent with the measured microstrip line loss of 0.74 $\mathrm{dB\,cm^{-1}\,GHz^{-1/2}}$.

In conclusion, CLD/APC based push–pull EO polymer MZ modulators with a $V_\pi L$ product of 2.4 and 3.6 V at 1310 and 1550 nm, respectively, were demonstrated. It is important to pole the polymer in a N_2 atmosphere to prevent chromophore bleaching. The poling alignment was earlier observed to be stable over the short term at 120 °C. Long-term thermal stability of the push–pull modulators at 60 °C in air was measured and an approximate 20% increase of V_π was observed after 65 days.

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