Electro-optic polymer modulators with 0.8 V half-wave voltage

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We report the fabrication and test results for polymeric electro-optic modulators with a half-wave voltage of 0.8 V and a half-wave voltage-interaction length product of 2.2 V cm. These modulators employ an optical push–pull architecture and are made from poly(methylmethacrylate) with a high molecular hyperpolarizability polyene bridge-type chromophore. An electro-optic coefficient of 58 pm/V was obtained at a 1318 nm wavelength. The guest–host polymer system exhibited a thermal stability to 75 °C and a relatively stable nonlinearity at ambient conditions. The experimental results have demonstrated not only the sub-1 V half-wave voltage electro-optic polymer modulator but also the potential of polymeric electro-optic materials for photonic applications. © *2000 American Institute of Physics.* [S0003-6951(00)01227-4]

Electro-optic (EO) modulators are widely used in broadband fiber-optic communication systems due to their well-defined transfer functions, large output optical power, wide modulation bandwidth, high extinction ratio, and low wavelength dependence. Current commercial EO modulators have half-wave voltages (V_π), typically in the range of 3–5 V so that broadband amplifiers are required to drive the modulators. As the communication bandwidth increases, it is desired to have modulators with low driving voltages (<1 V) because high-power, broadband amplifiers are very costly and require careful thermal management.

Traditional EO materials such as $LiNbO_3$ can achieve low V_π at low frequencies or for narrow bandwidths. For broadband traveling-wave modulators, the half-wave voltage-interaction length product $V_\pi L$ is limited at 10 V cm due to velocity and impedance-matching requirements.[1] Low V_π was obtained from increased interaction length.[1,2]

EO polymers are well known for their low dielectric constants and excellent velocity match between optical-wave- and microwave-modulation waves. High-speed, wide-bandwidth EO polymer modulators have been demonstrated with simple microstrip line electrodes.[3–5] However, the best previously reported V_π values without an active poling bias voltage applied were on the order of 3.5–5 V for polymer modulators.[6–8] The recent advances in the theoretical modeling of chromophore interactions and material synthesis have resulted in many new second-order nonlinear optical chromophores with high molecular hyperpolarizability and improved molecular alignment properties.[8,9] In this letter, we report the fabrication and experimental results of 0.8 V V_π EO polymer modulators with a $V_\pi L$ product of 2.2–2.4 V cm based on a highly nonlinear CLD-1 chromophore[10,11] and a highly efficient optical push–pull modulator architecture.[12]

The key enabling material in this modulator was a polyene bridge-type second-order nonlinear chromophore CLD-1 used as a guest molecule in a poly(methylmethacrylate) (PMMA) host. The molecular structure of CLD-1 is illustrated in Fig. 1. Tert-butyldimethylsilyl (TBDMS) groups were attached to the π-conjugation system to improve chromophore solubility and reduce dipole–dipole interactions between chromophores. These bulky groups prevent chromophores from getting too close to each other to form centrosymmetric aggregates. High chromophore concentrations can be achieved even in a guest–host polymer system. EO coefficient of 85 pm/V at 1064 nm was reported from corona-poled CLD-1/PMMA guest–host films.[11]

We have used a modified optical push–pull Mach–Zehnder modulator architecture in modulator design, as shown in Fig. 2. The push–pull architecture improves modulation efficiency by 6 dB because it can reduce V_π by a factor of 2 when compared with single-arm modulation at the same interaction length. In our devices, two lower electrodes were first fabricated on fused-silica substrates using photolithography methods. A polyurethane lower cladding 3.1 μm thick was spin coated and cured in steps up to 140 °C. Waveguide channels (6 μm wide) were etched into the lower cladding by oxygen plasma reactive ion etching. Etch depth was

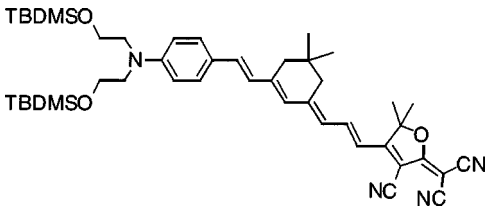

FIG. 1. Molecular structure of CLD-1 chromophore.

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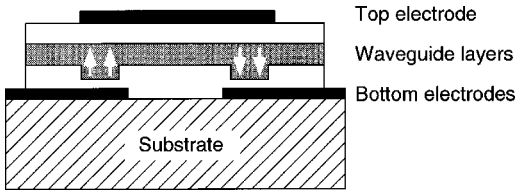

FIG. 2. Cross-sectional view of two waveguide channels (gray area) and three-section electrodes (black area) of a modified optical push–pull Mach–Zehnder modulator. The white arrows indicate the molecular alignment directions.

on the order of 0.5–0.6 μm. A 1.4 μm guiding layer was then spin coated on the patterned surface using 30 wt% CLD-1/PMMA in 1,2-dichloroethane solution. After drying and solvent elimination, a Norland 73 layer of approximately 3 μm was spun and cured under ultraviolet light from a xenon lamp. A top electrode was deposited by thermal evaporation. The polymer waveguide samples were diced and polished before poling to permit moderately low-loss coupling of light to the active waveguides. Two fused-silica end pieces were glued to each waveguide sample to ensure a flat endface.

The samples were poled on a laboratory-fabricated heater controlled by an Omega CN3201 temperature controller. The samples were first heated to 90 °C and gradually cooled down to 85 °C (measured at the top surface of the heater). Dc voltage in the range 500–750 V was applied to two lower electrodes, shown in Fig. 2, starting at approximately 87 °C. The poling current was monitored by a Keithley 485 current meter and was, typically, 80–150 nA, depending on the electrode length. No protective gas was used during electric-field poling. Because the high-voltage poling electrodes were covered by polymer layers, the dielectric breakdown between the electrode gap was eliminated at the poling voltage in our modified optical push–pull design. After cooling down to room temperature and removing the dc poling voltage, the poled sample was mounted on a waveguide device test bed for V_π measurement.

The V_π measurement setup consisted of a diode-pumped Nd:YAG at 1318 nm wavelength as the optical source, a calibrated HP81521B detector head with an HP8152A power meter as the photoreceiver, and an HF 8116A function generator as the driving source. The input beam was butt coupled to the modulator waveguide directly from a polarization-maintaining fiber, while the waveguide output was lens coupled to the photodetector head. The driving voltage was applied to the top electrode and the two lower electrodes were grounded. The output signal from the power meter was displayed on a LeCroy 9410 digital oscilloscope. A typical output wave form from the V_π measurement is shown in Fig. 3, where channel 1 (bottom trace) is the overdriven modulator output wave form and channel 2 (top trace) is the driving signal wave form. To accurately measure V_π, two pairs of cursors were positioned along the modulator output wave form to maximize the peak-to-valley voltage differential on channel 1. The corresponding channel 2 reading was taken as the measured V_π value. As shown in Fig. 3, the V_π for the recorded modulator was 0.767 V. We have measured all available modulators on the same chip, and the distribution of the measured V_π is shown in Fig. 4 for modulator chips with 3- and 2-cm-long interaction lengths. The measured V_π distribution was quite uniform across the modulator chips. The average V_π for the 3-cm-long interaction length modulator poled at 500 V was 0.819 V, with a best result of 0.767 V. For 2-cm-long interaction length modulators poled at 750 V, the average was 1.078 V. The half-wave voltage-interaction length product $V_\pi L$ was approximately 2.4 and 2.2 V cm, respectively, for the 3 and 2 cm electrode modulators. From the average measured V_π and the total layer thickness of the 3 cm electrode device, an EO coefficient of 58 pm/V at the 1318 nm wavelength was derived for the CLD-1/PMMA system. It should be noted that without optical push–pull, nearly a 120 pm/V EO coefficient is required to achieve the same result.

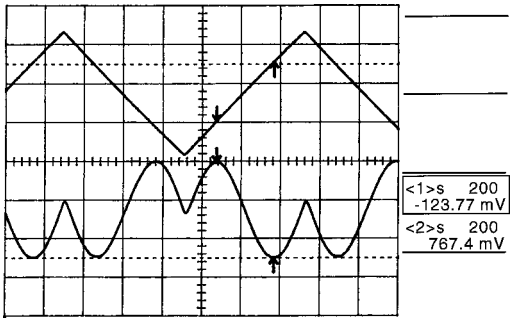

FIG. 3. Output wave form of the driving signal (top trace, channel 2, 0.5 V/div) and modulator output (bottom trace, channel 1, 50 mV/div). Half-wave voltage of 0.767 V is shown in channel 2 readout. The horizontal scale is 0.5 ms/div.

A major concern for the guest–host polymer system was the thermal and temporal stability of the molecular alignment. Fast decay has been reported in Disperse Red 1/PMMA guest–host systems.[13] However, in the CLD-1/PMMA system, a relatively stable EO response was obtained. Only ~15% decay was observed over a period of 1200 h, as shown in Fig. 5. Temperature ramping experiments at 10 °C/min showed a dynamic temperature stability (temperature at which loss of EO activity is first observed) of 75 °C. When compared with other PMMA guest–host systems, the CLD-1/PMMA system demonstrated a much improved chromophore alignment stability, which can be attributed to the bulky size of the chromophore. The thermal stability can be further improved when a high-glass-transition-temperature polymer matrix, such as a polyimide,[14] is used, or the chromophores are covalently attached to crosslinkable polymer matrices.[15]

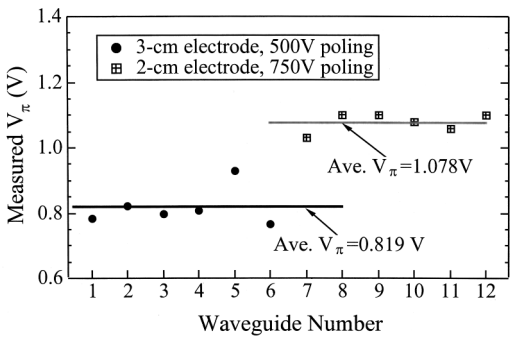

FIG. 4. Distribution of the measured half-wave voltage across modulator chips with 3 and 2 cm interaction lengths.

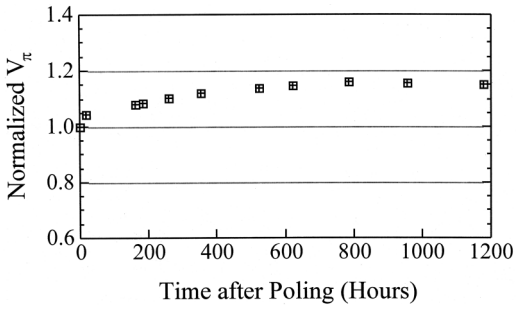

FIG. 5. Normalized temporal stability of a typical CLD-1/PMMA modulator at ambient conditions.

The CLD-1/PMMA guest–host polymer waveguide has a moderate intrinsic propagation loss at the 1300-nm-wavelength range. The waveguide loss measured in a slab waveguide was in the order of 0.8–1.2 dB/cm using the sliding liquid prism method.[16] For the channel waveguide modulators in our experiment, the best insertion losses in our poled chips (3-cm-long propagation) were 10 dB for a Mach–Zehnder modulator and 7 dB for a straight channel waveguide with input/output coupling losses excluded. A waveguide loss of 2.3 dB/cm was obtained in a straight channel waveguide. There are several factors that may contribute to the excess waveguide loss. In our experiment, we noticed insufficient lateral confinement in the waveguides. The driving circuit electrodes may also contribute to the excess waveguide loss. These losses can be significantly reduced by increased waveguide confinement in both lateral and vertical directions. Research efforts are currently underway to reduce optical insertion loss for our waveguide structure.

Although our modulator test was not performed at high frequency due to the initial electrode design, the push–pull electrodes we used can be easily modified to a microstrip line electrode with a slot ground structure.[17] The details of the broadband electrode design and modeling will be discussed elsewhere.

In conclusion, a 0.8 V V_π and a 2.2 V cm $V_\pi L$ product were achieved in a CLD-1/PMMA guest–host EO polymer modulator using the optical push–pull architecture. An EO coefficient r_{33} of 58 pm/V at the 1318 nm wavelength was obtained from the measured V_π value. The thermal and temporal stability of the poled modulators was monitored, and the insertion loss of the devices was characterized. Because the CLD-1 polymer system can be further optimized and chromophores with even higher molecular polarizability are available,[11] the experimental results in this work demonstrated not only the sub-1 V EO polymer modulator but also the potential for even lower V_π using polymeric materials in the future.

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