Replica-molded electro-optic polymer Mach–Zehnder modulator

George T. Paloczi,[a] Yanyi Huang, and Amnon Yariv
Department of Applied Physics, California Institute of Technology, Pasadena, California 91125

Jingdong Luo and Alex K.-Y. Jen
Department of Materials Science and Engineering, University of Washington, Seattle, Washington 98195-2120

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A Mach–Zehnder electro-optic polymer amplitude modulator is fabricated by a simple and high-throughput soft-stamp replica-molding technique. The modulator structure incorporates the highly nonlinear and stable chromophore, AJL8, doped in amorphous polycarbonate. Single-arm phase-retardation results in a halfwave voltage (V_π) of 8.4 V at 1600 nm. The on/off extinction ratio is better than 19 dB, resulting from precise Y-branch power splitters and good waveguide uniformity. These results indicate that the simple fabrication process allows for good optical performance from high-fidelity replicas of the original master devices. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1787944]

Organic nonlinear optical materials have been the subject of significant recent technological advances with the aim of commercial deployment, especially for telecommunications applications.[1] Polymers for integrated optical circuits exhibit several advantageous features. The raw materials are lower cost than their crystalline and semiconductor counterparts and offer more flexible fabrication methods.[2] Electro-optic polymers have low material dispersion, and thus low velocity mismatch between optical signals and microwave modulation, allowing electro-optic modulation bandwidths up to 1.6 THz.[3] The chromophore dopants responsible for the nonlinear optical characteristics are devised to achieve high nonlinearities, allowing for modulators with switching voltages of less than 1 V.[4] Recent advanced chromophore design has resulted in the development of highly nonlinear chromophores with good thermal- and photo-stability.[1] Shown in Fig. 1 is the chemical structure of one such chromophore, referred to as AJL8.[5] Films of AJL8 doped in an amorphous polycarbonate matrix exhibit a very high r_{33} value of 94 pm/V at 1300 nm. The onset degradation temperature was found to be 220 °C and around 80% of its original r_{33} value maintained very constantly for more than 500 h at 85 °C.[5]

Since electro-optic polymers are not generally photocurable themselves, fabrication of polymer modulators has been mostly limited to traditional semiconductor etching techniques such as reactive ion etching. An alternative fabrication technique that takes advantage of the plastic nature of electro-optic polymers is soft-stamp replica-molding lithography.[6] The main benefits of this technique are the simple and high-throughput fabrication (single-step structure formation), the low fabrication set-up costs, and the ability to replicate nanometer-scale structures over many square centimeters. In this technique, waveguide structures are formed by the molding of the core polymer using a soft stamp. Materials fabricated by this method can be either photo-curable, due to the transparency of the stamp material to ultraviolet light, or solidified by solvent evaporation, made possible by the permeability of the stamp material to common polymer solvents. Previously, this technique has been employed to make optical couplers[7] and polymer distributed feedback and distributed Bragg reflector lasers[8] for use in the visible regime. For infrared applications, this technique has been applied to optical interconnects[9] and microring resonator optical filters.[10] In this letter, we demonstrate the use of the replica molding technique for the fabrication of electro-optic polymer amplitude modulators.

The first portion in the replica molding process, shown in Figs. 2(a)–2(c), is the production of a mechanically flexible poly(dimethysiloxane) (PDMS) stamp. Because of the low surface energy of the elastomer stamp material, the master device to be replicated can be made of many commonly used resist, glass, or semiconductor materials. Ultraviolet lithography of photoresist is frequently used for patterning the master device. For smaller and higher resolution structures, electron beam lithography can be used. Liquid PDMS is poured atop the master structure and cured for 2 h at 80 °C. The cured PDMS stamp is peeled from the master device and diced to the required size. Since the curing and peeling of the PDMS stamp does not alter the original master, the master can be used to make additional stamps by repeating the preceding steps.

The replication procedure is shown in Figs. 2(d)–2(f). Similar to the case of the master device, the low surface adhesion and the chemical inertness of the PDMS allow virtually any polymer material in many solvents to be used for the replication. A droplet, tens of μL in volume, of the core

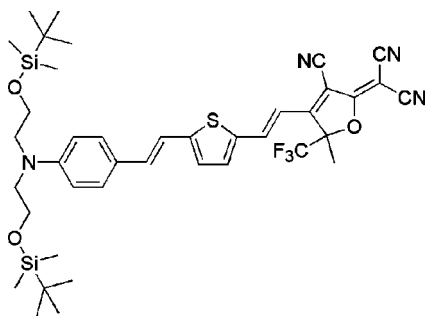

FIG. 1. Chemical structure of AJL8 chromophore.

[a]Electronic mail: paloczi@caltech.edu

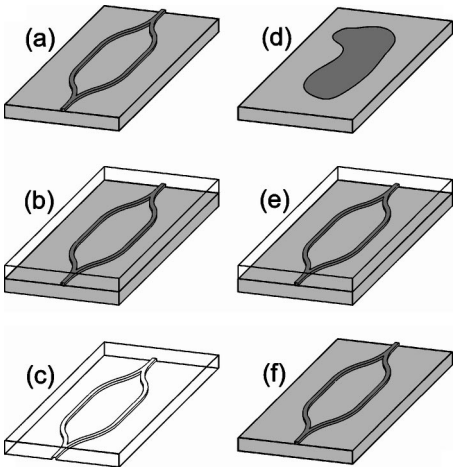

FIG. 2. Fabrication of the PDMS stamp (a)–(c) and replication (d)–(f). A master MZI device (a) is patterned by photolithography of SU-8. PDMS is poured on the master device (b), cured, peeled, and diced (c). A drop of electro-optic core solution is placed on the appropriate substrate (d). The PDMS stamp is depressed (e) until the core polymer is cured. The stamp is peeled to reveal the high-fidelity replicated device (f).

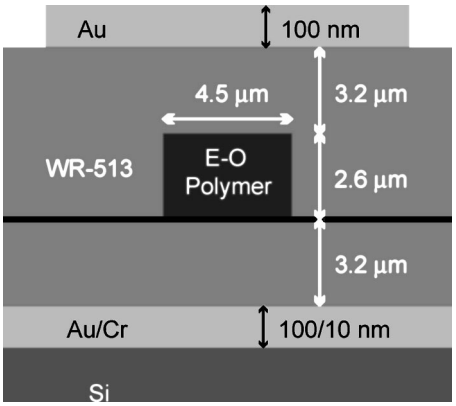

FIG. 3. Cross-sectional view of the electro-optic waveguide structure. The core electro-optic polymer is AJL8/APC and the upper and lower cladding materials are low refractive index epoxy WR-513.

polymer solution is placed on an appropriate substrate. The PDMS stamp is depressed on the solution/substrate, while monitoring the force with a force gauge. The force applied should be sufficient to ensure conformal contact between the stamp and the substrate, however, previous results suggest that the molded features are relatively immune to variations in pressure, so the actual force beyond what is required for conformal contact is not relevant.[11] After the solvent of the core polymer solution has evaporated through the PDMS, the stamp is removed from the substrate, revealing a high-fidelity replica of the original master device.

The structure patterned by replica molding is a Mach–Zehnder interferometer (MZI), shown schematically in Fig. 2. A Y junction equally divides the input light between the two arms of the interferometer and another Y junction combines the light having traversed two different optical path lengths. Each Y junction consists of two S-shaped bends with bend radii of 1 mm, ensuring low radiation loss. The interferometer arms are 2 cm in length. The MZI masters are exposed by photolithography of SU-8 (Microchem), a negative novalac epoxy resist, on a silicon substrate. The masters are baked at 150 °C for 1 h to smooth nanometer scale sidewall and surface imperfections. Two complete MZI structures comprise each mold, with a total mold size of 3.8 $\times$1.8 cm.

The core polymer is composed of the aforementioned AJL8 chromophore as the nonlinear optical dopant in amorphous polycarbonate (APC, Aldrich). APC has been shown to have excellent thermal stability as a polymer host material.[1] The ratio of chromophore to passive polymer was 20 wt% as in Ref. 5. A final solution concentration of 1.6 wt% was achieved by dissolving the solid in dibromomethane, yielding a solution with a moderate evaporation rate appropriate for the replica molding process.

The cross-sectional view of the replica molded electro-optic waveguide structure is shown in Fig. 3. The silicon substrate is coated with Cr and Au, serving as the bottom electrode. A lower cladding layer is necessary to optically isolate the guided light from the metal electrode. The challenge in choosing low refractive index polymer for the lower cladding is that it must be chemically resistant to the core polymer solution solvent. There exists a similar difficulty with the upper cladding polymer as its solvent must dissolve neither the core polymer nor the lower cladding. A commercial UV curable epoxy, WR-513 (Luvantix), with a refractive index of 1.50, is spun to a thickness of 3.2 μm for the lower cladding. The film is cured under an UV lamp for 5 min and baked at 100 °C for 2 h to lattice-harden the film, ensuring resistance to the solvent of the electro-optic polymer solution. The MZI structure is molded as described earlier. The width and thickness of the molded waveguide core is 4.5 and 2.6 μm, respectively. Due to the process of molding with a soft stamp, a thin residue of electro-optic polymer material is present; however, this residue can be controlled and maintained at a tolerable level.[11] The structure is baked at 100 °C for 2 h to remove any remaining solvent. Another 3.2-μm thick WR-513 film is spun on as the upper cladding. Finally, 100 nm of Au is evaporated over one arm of the MZI, serving as the upper electrode.

The randomly oriented chromophores dispersed in the APC matrix must be aligned to result in a collective electro-optic effect. By heating the polymer film above its glassy temperature ($T_g \approx 145$ °C for AJL8/APC) while applying a strong electric field, the dipolar chromophores are aligned. We employ the corona poling method[12] with a needle-to-sample separation of 2 cm. The needle tip is biased to approximately 5.6 kV. As the sample is heated to 145 °C, the corona current is monitored by measuring the voltage drop across a 10 MΩ resistor and is limited to 2 μA in an ambient air environment. The sample is poled for approximately 45 min, and then cooled while keeping the voltage applied. At $\sim$40 °C, the voltage is turned off and the sample is removed.

To prepare for measurement, the substrate is cleaved and the waveguide end-facets are left unpolished. Laser light at 1600 nm wavelength is fed through a polarizer and input into the MZI through a tapered fiber. The output signal is collected using another fiber and is measured using a photodetector. The voltage is applied to the MZI using either a voltage source or a function generator. The entire setup is controlled by GPIB.

The measurement results are shown in Fig. 4. Voltages ranging from -40 to $+40$ V are sequentially applied in 0.25 V increments while monitoring the photodetector output signal. The measurement was also confirmed using a 1 kHz triangle wave and an oscilloscope. With no applied

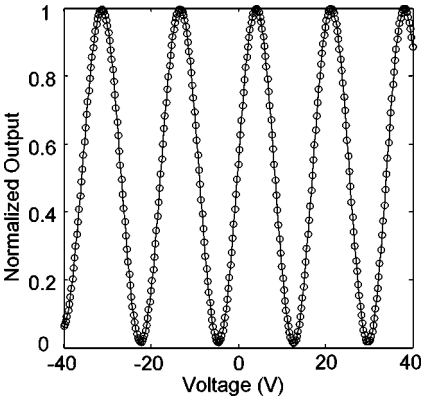

FIG. 4. Measured modulator output as a function of applied voltage.

voltage, the output is approximately half its maximum, indicating that the two arms of the interferometer are of slightly different length. The half-wave voltage V_π, defined as the voltage required to switch the output from full-on to full-off, is found to be 8.4 V. This value is within a factor of 2 of commercial devices, and several means can be employed to further reduce this value. First, thinning of the cladding layers would proportionally reduce V_π. Second, the voltage was applied to only one arm of the MZI, not to both arms in a push–pull fashion, which would result in a factor of 2 reduction in V_π. Finally, optimization of the poling efficiency is necessary to further reduce V_π. The total insertion loss was not measured since the waveguide end-facets were left unpolished and were not mode-matched to the input/output fibers.

While the halfwave voltage is indicative of the polymer nonlinearity and the electrode configuration, the on/off extinction ratio of the modulator signifies the quality and precision of the fabrication. In the MZI structure, light interferes after having traveled different optical path lengths and the degree of destructive interference depends on the quality of both the Y-junction splitter and combiner, and on any differential loss in the arms of the MZI. The extinction ratios of the nulls in the output shown in Fig. 4 are better than 19 dB, similar to recent reports using traditional electro-optic polymer fabrication techniques.[13] The deep extinction of the nulls for the replica molded MZI suggests that the Y junctions are of precise 3 dB splitting ratio and that there is very little differential loss in the interferometer arms. This demonstrates the accuracy of the replication process enabling high-resolution features of the Y junction to be reproduced in the replica. The achieved low differential loss indicates that the replica molding process produces a low number of waveguide defects and good waveguide uniformity over many square centimeters.

In summary, a Mach–Zehnder electro-optic polymer modulator was fabricated by soft-stamp replica-molding. The core polymer incorporated state-of-the-art nonlinear optical chromophores that are highly nonlinear and show good thermal- and photo-stability. The resultant device was measured with 1600 nm incident light to have a halfwave voltage of 8.4 V and an extinction ratio better than 19 dB. These results establish that the replica molding process has the potential to meet the demanding requirements of high-resolution necessary for inexpensive mass production of electro-optic polymer modulators.

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