Optically heterodyned 25-GHz true-time-delay lines on thick LD-3 polymer-based planar waveguides

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Synthesis of the LD-3 electro-optic polymer has resulted in a highly reliable nonlinear organic material. Such a success has been impeded from further progress because the LD-3 films produced thus far are too thin (<0.5 μm) to form a waveguide. Further details of material synthesis have to be studied to solve this problem. We report the formation of thick LD-3 films ranging from 1.2 to 2.4 μm by introducing cyclopentanone as the new solvent in polymer synthesis. The formation of multimode planar waveguides on silicon with a waveguide loss of approximately 1.3 dB/cm at 1.3 μm is demonstrated. Preliminary studies aimed at forming true-time-delay lines are conducted by use of various waveguide lengths in conjunction with an optical heterodyne technique. Waveguide settings equivalent to different true-time-delay lines with a delay time of up to 0.27 ns and a base bandwidth of 25 GHz are demonstrated with a signal-to-noise ratio of 15 dB.

As the speed of individual integrated-circuit components increases steadily and more electronic components are integrated into an ever-shrinking silicon real estate, an electrical interconnect over 1 cm becomes impractical for data rates above 1 GHz because of skin effect, propagation delay, and clock skew.[1,2] Optical interconnection offers a promising alternative by which one can avoid the common problems of impedance mismatch, the parasitic effects, and the bandwidth limit of the interconnect at such high data rates. Optical waveguides are routinely employed as the physical layers to carry and transfer high-speed optical signals. As compactness becomes essential for system integration, waveguiding materials that also exhibit electro-optic (EO) properties are of great importance because they have the potential to form functional integrated optical circuits. Polymeric materials have the advantage of exhibiting extremely fast nonlinear optical (NLO) response times because of the low dielectric constant compared with that of their inorganic counterparts.[3,4] Lower-velocity mismatch between the microwaves and the optical waves leads to the success of high-bandwidth modulators.[5] High-performance, EO NLO polymeric materials for use in photonic devices are under intensive research.[6,7] However, most NLO polymer materials are not suitable for real applications simply because they cannot simultaneously meet the three important requirements, namely, long-term stability, large EO coefficients, and material processibility, to make thicker films.

Polymeric materials have to meet the stringent thermal-stability requirements in order to be used for device applications. For some applications, a device operating temperature of up to 125 °C and a storage temperature as high as 120 °C are required.[8] A long-term stability at a temperature of 125 °C is the minimum requirement for military applications.[8] Many EO polymers have been synthesized in recent years. Some had very high EO coefficients (as high as 90 pm/V) but decayed relatively quickly, while some showed very high stability, but a very low EO coefficient.[9] Only a few materials have shown both good thermal stability (>100 °C) and reasonable magnitude of second-order nonlinearity[10,11] (γ_{33}>10 pm/V at λ = 1.3 μm). Among the acceptable ones, LD-3 turns out to be one of the best candidates in both categories.[12] It is stable up to 170 °C during the temperature scan of 10 °C/min. Long-term stability showed that after 1250 h at 125 °C, LD-3 still retained ~90% of its γ_{33} value.[13] However, material processibility of the LD-3 polymer prohibits the formation of thicker films needed for guided-wave device implementations.

In this paper we report for what is, to our knowledge, the first time the formation of a planar struc-

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ture waveguide made from LD-3 polymer films ranging from 1.2 to 2.4 μm. The excellent stability of the EO property of the LD-3 polymer stems from fixing the aligned dipoles in the polymer network by a cross-linker. This process requires the dissolving of the polymer chromophore and a cross-linker in a common solvent. After spin coating, the solvent should be easily removed without the processing of the material at elevated temperatures. Otherwise, a certain amount of cross-linking reaction might occur before the dipole is aligned by electric poling. This would result in either a reduction or a total disappearance of the EO coefficient. Therefore a compatible solvent must have the following characteristics: (1) good solubility but chemically inert to both LD-3 and the cross-linker; (2) no catalytic effect (i.e., it will not cause the polymer cross-linking in the solution); (3) proper solvent volatility for spin coating. This is important because a high-volatility solvent evaporates too quickly for thick films to be prepared. On the other hand, if the solvent evaporation rate is too slow, it is necessary to heat the film to remove the solvent, which is again undesirable.

Solvent tetrahydrofuran was suggested by some researchers.[11,13] However, because of the high volatility of tetrahydrofuran, it is impossible to make smooth films thicker than 0.5 μm.[14] Other solvents were tested but with little success. For example, cyclohexanone has low solubility to LD-3. Pyridine has a catalytic effect on the reaction between LD-3 and the cross-linker such that the solution is no longer spin coatable. Dimethyl sulfoxide is hard to be removed without inducing unwanted cross-linking. These detrimental effects that are due to the solvents make the fabrication of thicker EO films extremely difficult. In fact, since the successful synthesis of this material two years ago,[11] no guided-wave device based on LD-3 has been made because of the above-mentioned obstacles of forming thicker films. To make a guided-wave device, a high-quality film with a thickness larger than the cutoff thickness is required for supporting a fundamental model.[15] Furthermore, EO guided-wave devices usually need to be coupled with optical fibers or other waveguide devices. This requires that the thickness of the active layer of the polymer waveguide be comparable with the core diameter of the fiber to avoid severe coupling-loss penalties.

To find a solvent that has a good solubility to both LD-3 polymer and the cross-linker—dianisidine diisocyanale (Pfaltz & Bauer, Inc.)—we systematically followed the solvency screening procedure.[16] Figures 1(a), 1(b), and 1(c) illustrate the molecular structure of the LD-3, the cross-linker, and the solvent, respectively. Because the chromophore in the LD-3 polymer has a strong dipole moment and in every base unit of the polymer there are three hydroxyl groups, polar solvents with a mild or a strong hydrogen bond should be chosen. Solvents with the -NH or the -OH group are eliminated because they will react with the cross-linker. Vapor pressure at room temperature is used as the final criterion to narrow down the search.

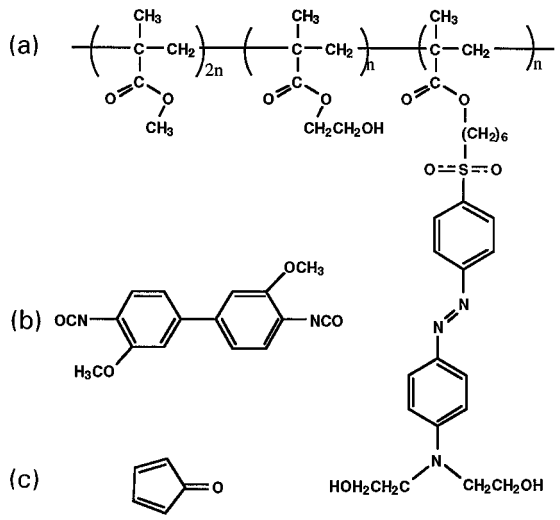

Fig. 1. Chemical structures of the LD-3 polymer solution system: (a) the LD-3 polymer, (b) the cross-linker, (c) the solvent.

After many iterations, cyclopentanone [Fig. 1(c)] was experimentally confirmed to be the best solvent for making high-quality thicker LD-3 films. Cyclopentanone exhibits high solubility to both LD-3 and the cross-linker, and it can be vacuum dried in a cleanroom house vacuum with no side reaction observed. By using cyclopentanone as the solvent, we have achieved an EO coefficient γ_{33} of corona-poled LD-3 polymer films comparable with the reported value.

LD-3-based planar waveguides are formed by spin coating a layer of LD-3 EO polymer on glass substrates. The guiding layer is formed between air and the glass substrate. Polymer films with thicknesses ranging from 1.2 to 2.4 μm are prepared. The film refractive index is measured to be 1.64 at 632.8 nm by the prism-coupling method. The spin-coated films show good uniformity and surface flatness. The transmission spectrum of a 1.2-μm LD-3 polymer thin film is measured. It is optically transparent from ~600 to ~3200 nm. Guided waves are excited by prism coupling. Figure 2(a) illustrates the propagation of the fundamental mode of a polymer planar waveguide that has a film thickness of 1.25 μm. From the guided-wave theory,[17] three guided modes are predicted for the waveguide with a film thickness of 1.25 μm, which is experimentally verified by the observation of guided-mode propagation at three different incidence angles on the input prism coupler. However, at the input-coupling angle corresponding to the fundamental mode, the far-field pattern shows three mode lines instead of a single-mode dot. This indicates that there is in-plane scattering accompanied by mode conversion.[18]

Waveguide loss is measured at the important telecommunication wavelength of 1.32 μm, which is evaluated from vidicon images of the light scattered out of the waveguide.[19] The loss of the waveguide on a glass substrate is found to be ~3 dB/cm. Such a large loss imposes limitations for making practical devices. To improve the loss figure, planar waveguides on a

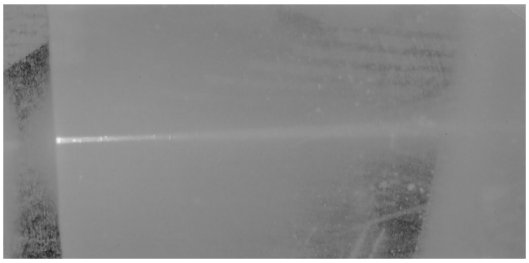

Fig. 2. Photograph showing the fundamental-mode propagation inside the LD-3 polymer waveguide that has a thickness of 1.2 μm at λ = 632.8 nm; the waveguide length is 4 cm.

silicon wafer with claddings are prepared, and the loss is much improved. Figure 3 illustrates the CCD image of the propagation of 1.3-μm light in the waveguide. The propagation of light from the center of a 4-in. (10.16-cm) wafer to the edge is clearly observable. Figure 4 shows that the loss at 1.32 μm is 1.3 dB/cm on a silicon substrate.

The discovery of using cyclopentanone as an appropriate solvent to provide thicker films helped us to demonstrate LD-3-based polymer waveguides for which a myriad of feasible applications can be implemented. These include high-speed waveguide modulators, optical-delay lines for phased-array feeders, and waveguide sensors. For optical-delay lines, the waveguide demonstrated can be structured to provide true-time-delay lines[20] with high-speed optical signals generated by an LD-3-based EO modulator or by optical heterodyne. In this paper, we have employed an optical heterodyne technique[21] to provide high-speed microwave signals from 1 to 25 GHz. Various lengths of LD-3-based planar waveguides corresponding to different true-time-delay lines[22] are tested to evaluate the transmission of optically heterodyned signals.

The high-speed baseband signal is generated by a optical heterodyne detection scheme in which the outputs from two lasers with wavelength separations from a subangstrom to hundreds of angstroms are collinearly mixed. This collinearly mixed signal is coupled into and out of the planar waveguide through prism couplers at different propagation lengths equivalent to different true time delays up to 0.27 ns (5 cm in length). The output is fed into an ultrafast

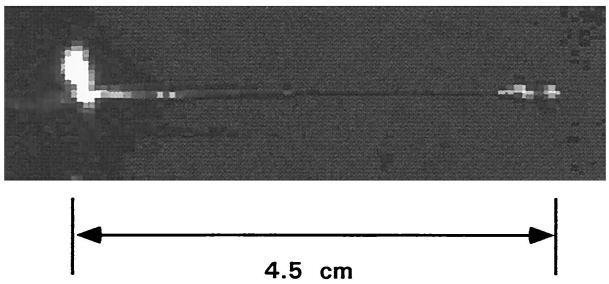

Fig. 3. CCD image of 1.32-μm light propagation on a waveguide made on a silicon substrate. Cladding material NOA61, lower cladding 3 μm, upper cladding 1 μm.

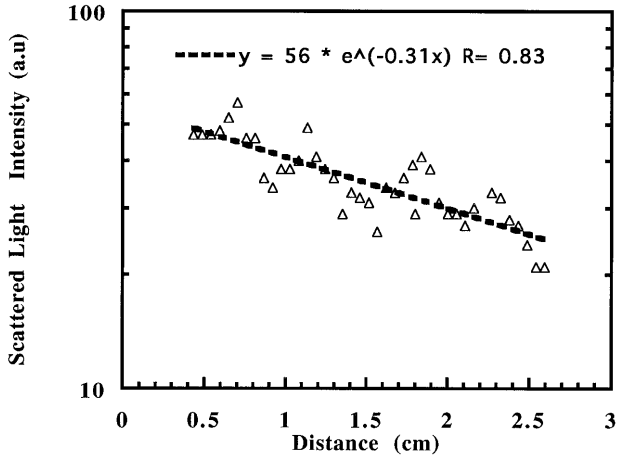

Fig. 4. Measured waveguide loss of LD-3 thin film (1.2 μm thick) on a silicon substrate at λ = 1.32 μm.

photodetector (PD) with a fiber-cable connector. The photocurrent output from the PD contains a dc part and an ac part corresponding to the high-frequency rf beat signal. If the optical fields of two separate lasers are given by $E_1 = A_1 \exp(j\omega t)$ and $E_2 = A_2 \exp[j(\omega) + \omega_{12})t]$, where ω_{12} is the beat frequency and the two lasers are linearly polarized in the same direction, the output of the PD in the form of a photocurrent is given by[23]

$$i_c(t) = \frac{e\eta}{h\nu}[A_1^2 + A_2^2 + 2F(\omega_{12})A_1A_2\cos(\omega_{12}t)]. \quad (1)$$

Here, e is the electron charge, η is the quantum efficiency of the detector, $h\nu$ is the incoming photon energy, and $F(\omega_{12})$ is the frequency response function of the PD. The optical-to-electrical conversion represented by Eq. (1) is equivalent to that of directly modulating a laser diode.[21]

Two tunable diode lasers (NewFocus 6124), with a central wavelength of ~786 nm, are stabilized by the current and the temperature controllers (NewFocus Model 6100). The linewidth of the laser is ~100 kHz. The outputs of the lasers are combined by a 50:50 beam splitter, pass an optical isolator, and then are coupled into the waveguide by a prism coupler at a suitable angle of incidence. The optical signal is coupled out of the waveguide through another prism coupler and then to a single-mode fiber with a 20× microscope objective lens. The output of the fiber is launched directly to an ultrafast PD (Picometrix PX-D7) with a 60-GHz bandwidth through the matched FC connector. The PD output is amplified through a broadband amplifier (NewFocus 1422) and immediately connected to a spectrum analyzer (HP8563E) for display. Figure 5 gives the 25-GHz rf signal detected by a spectrum analyzer. A signal-to-noise ratio of ~15 dB is obtained. Currently, 25 GHz is limited only by the frequency response of the amplifier and the spectrum analyzer used. If external mixers and a wideband amplifier are used, a much higher upper frequency[21] is expected.

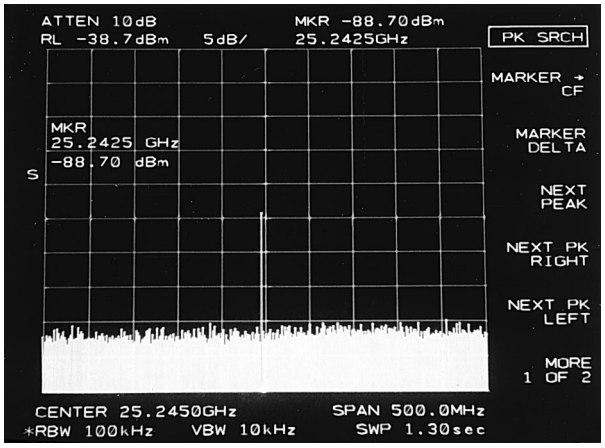

Fig. 5. 25-GHz optical heterodyne signal detected by a spectrum analyzer.

In conclusion, we report LD-3 EO polymer-based thin-film waveguides with a thickness of up to 2.4 μm. The LD-3 polymer-based planar waveguide is fabricated by spin coating an LD-3 optical polymer on top of a microscope slide glass substrate with cyclopentanone as the new solvent. Guided-mode propagation is investigated for the first time on LD-3 EO polymeric material. A waveguide loss of ~1.3 dB/cm is obtained on a planar waveguide made on silicon with cladding. Furthermore, LD-3 polymer waveguides are tested for transmitting high-speed optical signals generated by an optical heterodyne technique. True-time-delay lines with Δt up to 0.27 ns are realized by use of an LD-3-based polymer waveguide with various lengths in conjunction with an optical heterodyne in which microwave signals of up to 25 GHz were generated for the present demonstration. Realizing that such a thin-film layer can be implemented on any substrate of interest, we expect that reliable monolithic optoelectronic integrated circuits for the above-mentioned applications can be realized by adopting such an EO polymer on a common substrate.

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