Demonstration of planar waveguides on thick LD-3 polymer films for true-time-delay applications

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ABSTRACT

The successful synthesis of the LD-3 electrooptic polymer has resulted in a highly reliable nonlinear organic material. However, further progress has been impeded due to the fact that LD-3 films produced thus far are too thin (< 0.5 μm) to form useful waveguide devices. Here the formation of thick LD-3 films ranging from 1.2 μm to 2.4 μm by using cyclopentanone as the new solvent are reported. Preliminary waveguide loss studies shows a guide loss of approximately 3 dB/cm. Aimed at forming true-time-delay lines for phased-array antenna applications, optical heterodyne detection is conducted using various waveguide lengths. A heterodyne signal of a base bandwidth of 25 GHz is demonstrated with signal-to-noise ratio of 15 dB.

Keywords: EO polymer, LD-3, waveguide, optical interconnect, heterodyne detection, true-time-delay, phased array antenna

1. INTRODUCTION

High performance, electrooptic nonlinear optical polymeric materials for use in photonic devices are under intensive research.[1-2] Polymeric materials offer a much lower dielectric constant than their inorganic counterparts.[3-4] The resulting lower velocity mismatch between the microwaves and the optical waves has lead to the demonstration of high bandwidth modulators.[5] In addition, polymeric materials can be processed on virtually any substrates of interest with greater ease and versatility. However, in order to be used in real devices, an electrooptic polymeric material not only has to have a reasonable nonlinear coefficient it also has to meet the stringent thermal stability requirements. Commercial devices require an operating temperature up to 125 °C and a storage temperature as high as 120 °C. Although some polymers exhibit very high EO coefficient (as high as 90 pm/V [6]), this value deteriorates quickly. Others showed very high stability but with very low EO coefficient.[8] Only a few materials have shown both good thermal stability and reasonable magnitude of EO nonlinearity ($\gamma_{33}>10$ pm/V).[7-9] Among the acceptable ones, LD-3 [9-10] turns out to be one of the best candidates in both categories. Long term stability showed that after 1250 hours at 125 °C LD-3 still retained about 90% of its γ_{33} value.[11] However, material processibility of LD-3 polymer prohibits the

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formation of thicker (< 0.5 μm) films needed for guided wave device implementations due to the lack of a compatible solvent . To make a guided wave device from a polymer material, a high quality film with a thickness larger than the cut-off thickness is required to support a fundamental mode. Furthermore, EO guided wave devices usually need to be coupled with optical fibers or other waveguide devices. This requires the thickness of the active layer of the polymer waveguide be comparable to the core diameter of the fiber to avoid severe coupling loss penalties. In this paper, we report the formation of a planar structure waveguide made from LD-3 polymer films ranging from 1.2 μm to 2.4 μm. Waveguide features such as light propagation, mode structure and loss are evaluated. Aimed at forming optical true-time-delay lines optical heterodyne detection is conducted on various lengths waveguides. Base band signals up to 25 GHz are successfully achieved with a signal-to-noise ratio of 15 dB.

2. APPROACH AND EXPERIMENTS

The excellent stability of the EO property of LD-3 polymer stems from fixing the aligned dipoles in the polymer network by a crosslinker. This process requires to dissolve the polymer chromophore and the crosslinker in a common solvent. After spin-coating, the solvent should be easily removed without processing the material at elevated temperatures. Otherwise, certain amount of crosslinking reaction might occur before aligning the dipole by electric poling, which would reduce the EO coefficient or make it disappear totally. To preserve the EO property fixed after electric poling, a compatible solvent must have the following characteristics: 1) good solubility but chemically inert to both LD-3 and the crosslinker; 2) no catalytic effect during crosslinking; 3) proper solvent volatility for spin-coating. Solvent tetrahydrofuran (THF) was suggested by some researchers.[9,11] However, due to the high volatility of THF, it is impossible for smooth films thicker than 0.5 μm to be prepared.[12] Cyclohexanone has too low a solubility to LD-3 and pyridine has catalytic effect on the reaction between LD-3 and the crosslinker such that the solution can no longer be used for spin-coating. Dimethyl sulfoxide is hard to be removed without inducing unwanted crosslinking. To find a solvent which 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.[13] After many experimental iterations, cyclopentanone was determined 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 without side reaction.. Using cyclopentanone as the solvent, we have achieved EO coefficient γ_{33} of corona poled LD-3 polymer films comparable to the reported value.

LD-3 based planar waveguides are formed by spin-coating a layer of LD-3 EO polymer on glass substrates. Polymer films with thicknesses ranging from 1.2 μm to 2.4 μm are prepared. The film refraction index is measured to be 1.64 at 632.8 nm by the prism coupling method. The spin-coated film shows good uniformity and surface flatness. Measurements on the transmission spectrum (see Fig.1) of a 1.2 μm LD-3 polymer thin film shows an optically transparent window from ~540 nm to ~3200 nm. Figure 2(a) gives the propagation of the fundamental mode of a polymer planar waveguide having a film thickness of 1.25 μm. Propagation losses . at 1.3 μm are evaluated to be ≤ 3 dB/cm from CCD iamges of the light scattered out of the waveguide.[14] Three guided modes are experimentally observed, which is also predicted from guided wave theory.[15] Figure 2(b) shows the far-field mode pattern of the guided wave with an input coupling angle fixed at the angle corresponding to the fundamental mode. The existence of three mode lines instead of one mode dot shows strong in-plane scattering accompanied with mode-conversions.[16]

3. RESULTS AND CONCLUSIONS

A myriad of feasible applications based on LD-3 polymer waveguides can be demonstrated with thicker films. True-time-delay lines[17] for phased-array antenna applications is one of them. In this respect, various lengths LD-3 based planar waveguides with lengths corresponding to different true-time-delay lines are tested to evaluate the transmission of optically heterodyned signals from 1 GHz to 25 GHz. High speed baseband signal is generated by optical heterodyne detection scheme[18] in which the outputs from two lasers with wavelength separations from sub-Å to hundreds of Å are collinearly mixed, as illustrated in Fig. 3. Two tunable diode lasers, with a central wavelength around 786 nm, are stabilized by the current and temperature controllers. The line width of the laser is around 100 KHz. The outputs of the lasers are combined by a 50:50 beam splitter, passing an optical isolator and then coupled into the waveguide by a prism coupler at a suitable angle of incidence. Optical signal is coupled out of the waveguide through another prism coupler and then to a single mode fiber (SMF) with a 20 X microscope objective lens. The output of the fiber is launched directly to an ultrafast photodetector with 60GHz bandwidth through the matched FC connector. The PD output is amplified through a broadband amplifier and immediately connected to a spectrum analyzer for display. 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 photodetector in the form of photocurrent is therefore given by [19]

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

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. Figure 4 gives the detected 25 GHz rf signal by an spectrum analyzer. A signal to noise (S/N) ratio of ~ 15 dB is obtained. Presently, 25 GHz is limited only by the frequency response of the amplifier and the spectrum analyzer used. By using external mixers and wideband amplifier, much higher upper frequency [18] is expected.

In conclusion, LD-3 EO polymer-based thin film waveguides with a thickness up to 2.4 μm are reported for the first time. The LD-3 waveguides are fabricated by spin-coating on microscope slide glass substrates using cyclopentanone as the new solvent. Guided-mode propagation are investigated on LD-3 EO polymeric material. Furthermore, aimed at employing LD-3 polymer waveguides as true-time-delay lines, they are tested for transmitting high speed optical signals generated by optical heterodyne technique. For the present demonstration, microwave signals up to 25 GHz is generated and detected through LD-3 waveguides with signal to noise ratio of 15 dB.

4. ACKNOWLEDGMENTS

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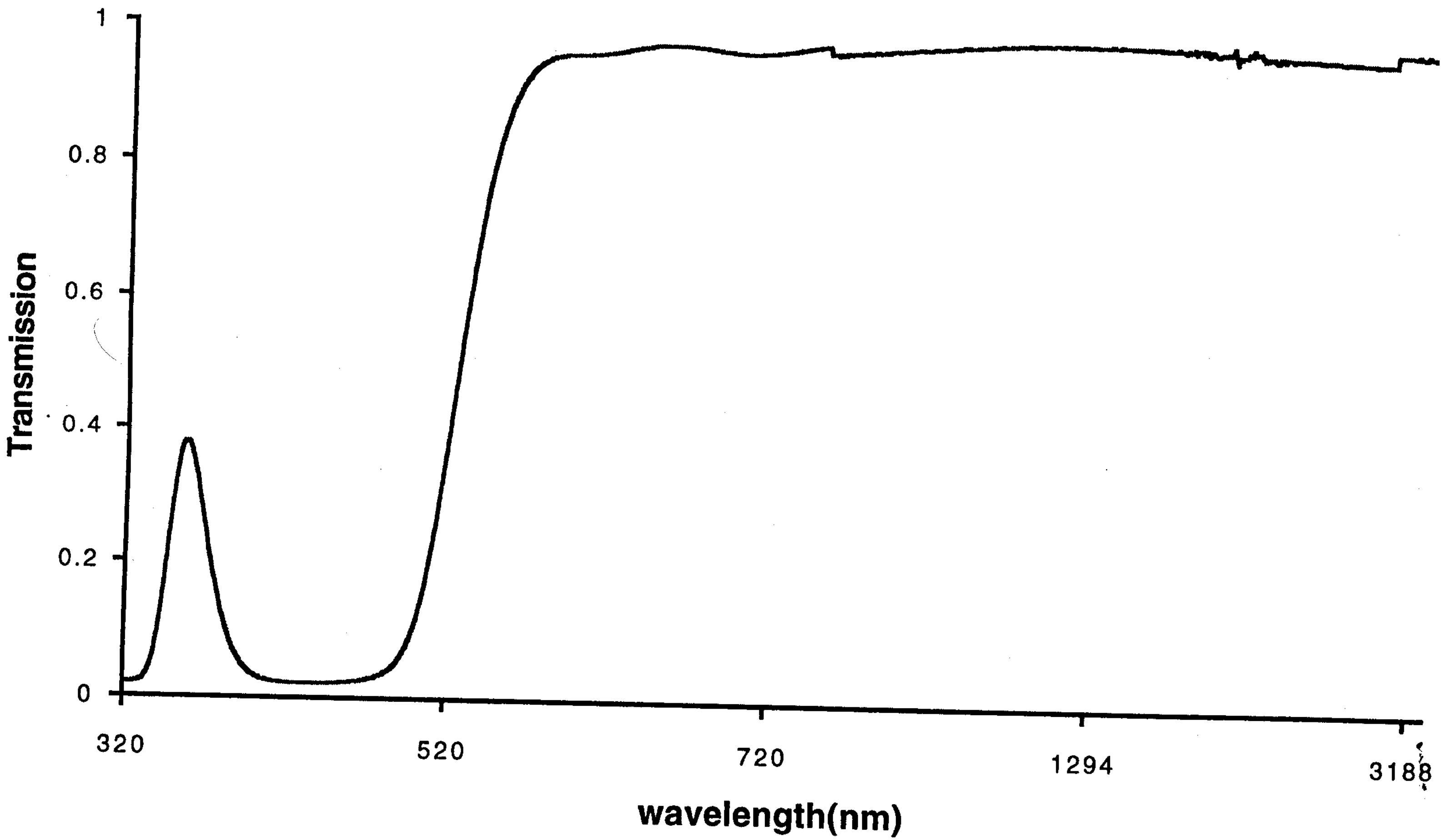
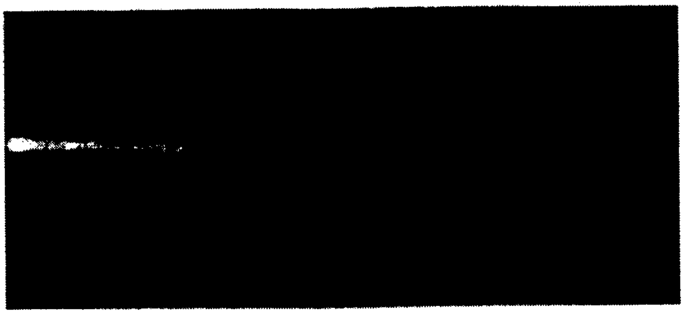
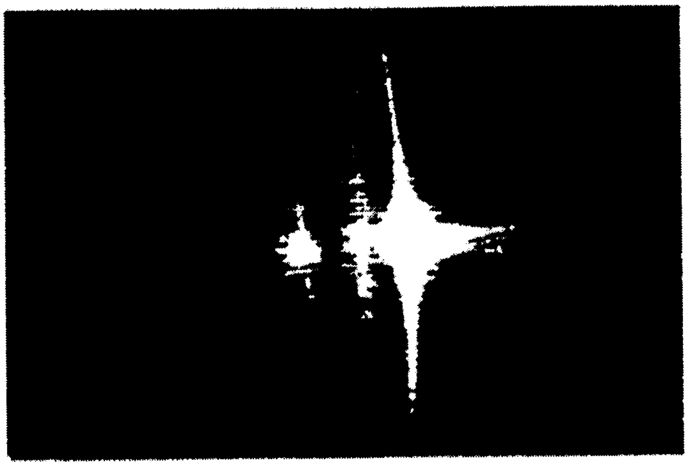


Figure 1 Transmission spectrum of the LD-3 polymer thin film (1.25 μm thick)



(a)



(b)

Figure 2 (a) Propagation of the fundamental mode inside the LD-3 polymer waveguide at at $\lambda=1.32\,\mu$m

(b)Far-field pattern of the guided modes coupled-out by a high-index prism

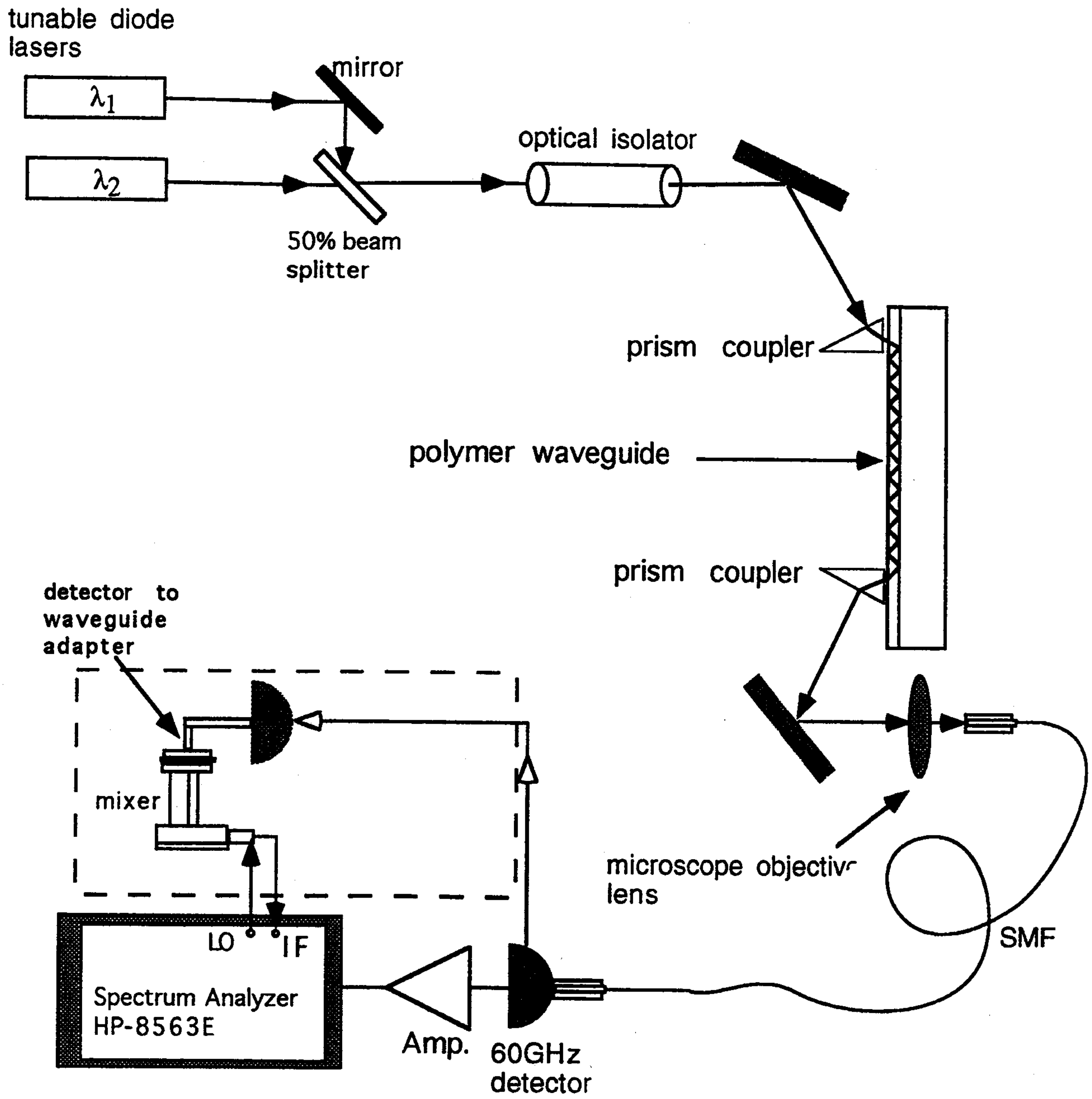
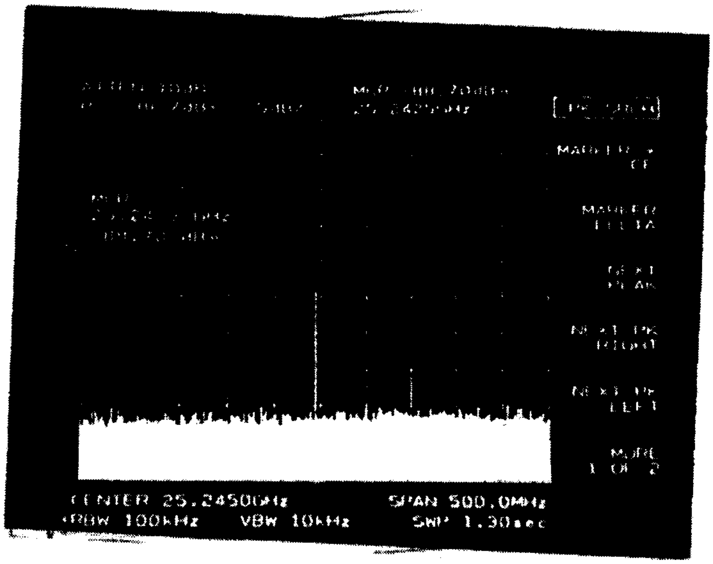


Figure 3 Optical heterodyne detection scheme



CENTER 25.2450GHz SPAN 500.0MHz
RBW 100kHz VBW 10kHz SWP 1.30sec

Figure 4 25 GHz optical heterodyne signal detected by an spectrum analyzer