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著者	Iiyama Koichi, Ishida Terumasa, Ono Yusuke, Maruyama Takeo, Yamagishi Tadaaki
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Fabrication and Characterization of Amorphous Polyethylene Terephthalate Optical Waveguides

Koichi Iiyama, *Member, IEEE*, Terumasa Ishida, Yusuke Ono, Takeo Maruyama, *Member, IEEE*, and Tadaaki Yamagishi

***Abstract*—Amorphous polyethylene terephthalate (PET) optical waveguides are fabricated by the spin coating method and the optical properties are characterized. The refractive index measured by a spectroscopic ellipsometer is 1.5656, 1.5560, 1.5489, and 1.5477 at 633-, 830-, 1310-, and 1550-nm wavelength, respectively. Multimode optical waveguides with 12-μm thickness and 46-μm width are fabricated by mechanical grinding using a dicing saw to form the core ridge, and the propagation loss is measured by the cut-back method to be 0.30, 0.12, 0.35, and 0.70 dB/cm for 660-, 830-, 1310-, and 1550-nm wavelength, respectively.**

***Index Terms*—Optical waveguide, polyethylene terephthalate (PET), polymer, polymer optical waveguide, propagation loss.**

I. Introduction

TRANSPARENT polymer thin films are very attractive for optical waveguides because of their flexibility, easy manufacturability and low-cost nature [1], and a number of polymers such as (fluorinated) polyimide [2], [3], poly-methylmethacrylate (PMMA) [4]–[6], polystyrene, polycarbonate and benzocyclobutene (BCB) [7], [8] have been investigated for optical waveguide applications. Some polymer optical waveguides exhibit low propagation loss below 0.5 dB/cm, and then polymer optical waveguides can be applicable to optical interconnection between integrated circuits or between printed circuit boards. In optical interconnection systems, a short wavelength light such as 650 nm or 830 nm wavelength will be used because the optical interconnection is a cost-effective system. Most of polymers are transparent in the short wavelength range and can be used as optical transmission materials in the optical interconnection systems.

Polyethylene terephthalate (PET) is a popular polymer material because it is widely used as soft-drink bottles. PET has some excellent performance such as very low-cost (cheaper than PMMA), chemically stable, good gas barrier performance, mechanically strong, and transparent in, at least, visible wavelength range. However, PET has not been actively examined as a material of the optical waveguides because of the low glass transition temperature (about 70°C) and the crystalline nature [9], [10]. When a PET film is fabricated by, for example, the spin coating method, the PET film tends to be partially crystallized and clouded during cooling after baking process, which may causes light scattering inside the PET film. In [11], PET films are formed on slide glasses by dip coating followed by baking with the temperature of less than 60°C, and the propagation loss in a slab optical waveguide is measured to be 0.7 dB/cm at 633 nm wavelength.

PET-G, which was developed by Eastman Kodak, is a kind of PET copolymerized with 1,4-cyclohexanedimethanol (CHDM), and is widely used as a coating film on integrated circuit (IC) cards. PET-G is perfectly amorphous, and then PET-G is a desirable material for optical waveguides [12].

Here we report fabrication and characterization of PET-G optical channel waveguides. Multimode waveguides are fabricated by mechanical grinding and the propagation loss was measured to be 0.30 dB/cm, 0.12 dB/cm, 0.35 dB/cm and 0.70 dB/cm for 660 nm, 830 nm, 1310 nm and 1550 nm wavelength, respectively.

II. Preparation and Characterization of PET-G Films

PET-G films were fabricated by the spin coating method. A PET-G solution is prepared by dissolving small PET-G pellets in ortho-chlorophenol (o-chlorophenol). The maximum PET-G concentration in the solution was 30 wt% by heating the o-chlorophenol to 100°C in an oil bath. However the solution has a high-viscosity and cannot be used for the spin coating when the concentration is more then 20 wt%. Hence the PET-G concentration is limited to less than 17 wt% in our study.

At first, we studied the thickness and the refractive index of the PET-G films by using a spectroscopic ellipsometer (J. A. Woollam Co. Inc., M-2000) with the measurement wavelength range of 246.4 $\sim$ 1668 nm. PET-G films were formed on Si substrates (size: 20 mm $\times$ 20 mm) by the spin coating followed by baking in an electric vacuum furnace at 200°C for 1 hour. The boiling point of the o-chlorophenol is 175°C in atmosphere.

Fig. 1 shows the thickness of the PET-G films against the rotation speed of the spin coating. The thickness increases according to the PET-G solution concentration, and the maximum thickness was 12 μm. In studies of chip-to-chip and board-to-board optical interconnections, multimode optical waveguides with the core thickness of 50 μm are widely used for easy optical coupling from the laser source or multimode optical fibers to the optical waveguides. The result shown in Fig. 1 indicates that 50 μm-thick multimode optical waveguide cannot be obtained by single spin coating, and can be obtained by multiple spin coating.

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K. Iiyama, T. Ishida, Y. Ono, and T. Maruyama are with the School of Electrical and Computer Engineering, Kanazawa University, Kanazawa 920-1192, Japan (e-mail: iiyama@ee.t.kanazawa-u.ac.jp).

T. Yamagishi is with the School of Chemistry, Kanazawa University, Kanazawa 920-1192, Japan.

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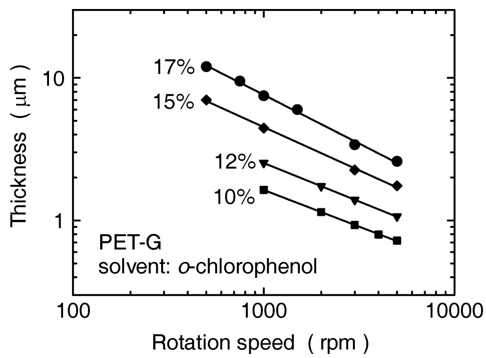


Fig. 1. Measured thickness of the PET-G film for various PET-G solution concentrations.

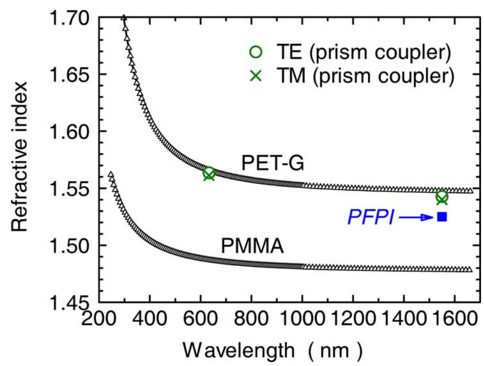


Fig. 2. Refractive index of the PET-G film measured by a spectroscopic ellipsometer and a prism coupler.

Fig. 2 shows the measured refractive index of the PET-G film along with the refractive index of a PMMA film. In the measurements, a 6 μm-thick PET-G film was formed on a Si substrate. The PMMA film was formed on a Si substrate by the spin coating, where propylene glycol monomethyl ether acetate (PGMEA) was used as the solvent of PMMA. In the spectroscopic ellipsometry, the refractive index is modeled by the Cauchy model, and the results are as follows;

$$n_{\text{PET-G}}(\lambda) = 1.5447 + \frac{0.006891}{\lambda^2} + \frac{6.000 \times 10^{-4}}{\lambda^4} \quad (1)$$

$$n_{\text{PMMA}}(\lambda) = 1.4768 + \frac{0.003937}{\lambda^2} + \frac{7.423 \times 10^{-5}}{\lambda^4} \quad (2)$$

where $n_{\text{PET-G}}(\lambda)$ and $n_{\text{PMMA}}(\lambda)$ are the refractive indices of the PET-G and the PMMA films, respectively, and the wavelength λ is in μm unit. In Fig. 2, the open triangles are the result by the spectroscopic ellipsometry for the PET-G and the PMMA films, and the closed square is the refractive index of perfluorinated polyimide (PFPI). Typical refractive index of the PET-G film is tabulated in Table I. The refractive index of the PET-G film is higher than that of the PFPI and the PMMA, showing that the PET-G film works as a core on the PFPI film or the PMMA film.

A 6 μm-thick PET-G film was formed on a SiO_2 glass and the refractive index of the PET-G film was also measured by using the prism coupler (Metricon Model 2010). The results are also shown in Fig. 2 as the open circles and the crosses for the TE and the TM modes, respectively, and in Table I. The PET-G film on SiO_2 glass supports 10 and 9 modes for the transverse electric (TE) and the transverse magnetic (TM) modes at 633 nm, respectively, and supports 4 modes for both the TE and the TM modes at 1550 nm. The difference between the two methods is less than 0.5%.

TABLE I
REFRACTIVE INDEX OF THE PET FILM ESTIMATED BY A PRISM COUPLER AND A SPECTROSCOPIC ELLIPSOMETER

Wavelength	Ellipsometer	Prism coupler TE mode	Prism coupler TM mode
633 nm	1.5656	1.5636	1.5612
830 nm	1.5560	—	—
1310 nm	1.5489	—	—
1550 nm	1.5477	1.5428	1.5400

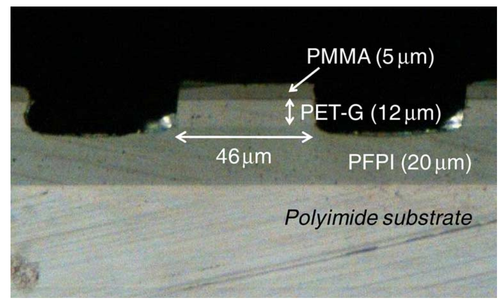
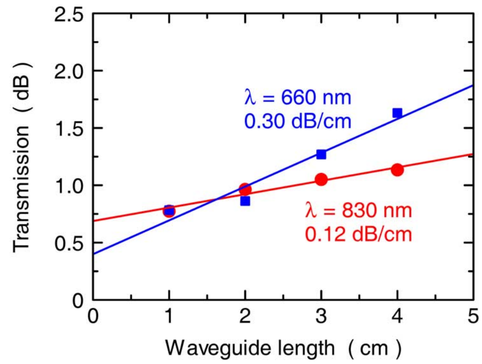


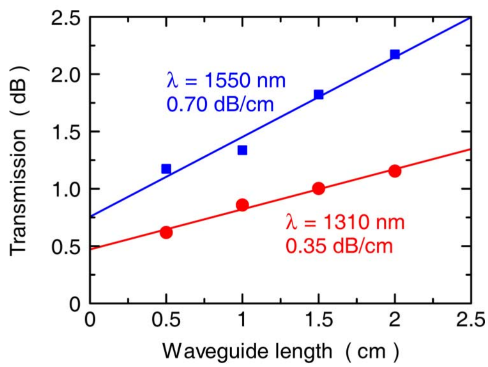
Fig. 3. Photograph of the facet of the PET-G channel waveguide.

III. CHARACTERIZATION OF PET-G CHANNEL WAVEGUIDES

The PET-G channel optical waveguide was fabricated and the propagation loss was measured by the cut-back method. The substrate used was a polyimide substrate, on which a 20 μm-thick PFPI was coated as a transparent under cladding, which was prepared by NTT Advanced Technology Corporation. The PET-G concentration in the solution was 17 wt% and the rotation speed of the spin coating was 1500 rpm, which results in 6 μm-thick PET-G film. A thicker PET-G film was fabricated by three-times multiple spin coating. A 5 μm-thick PMMA film was then coated on the PET-G film by the spin coating followed by vacuum baking at 200°C using the PMMA solution dissolved in PGMEA. The core ridge was then formed by mechanical grinding using a dicing saw. The grit size of the dicing blade was #5000. Finally, the waveguide was cut by a dicing saw to achieve smooth facets for the optical input and output. The PMMA film on the PET-G film is useful to avoid damage on the surface of the PET-G film during the dicing process because of strong cooling water to the dicing blade. The photograph of the facet of the PET-G waveguide is shown in Fig. 3. Three layers (PFPI, PET-G and PMMA layers) can be clearly shown on the polyimide substrate. The thickness of the PET-G film is 12 μm and is thinner than the expected thickness of the three-times multiple spin coating (18 μm $=$ 6 μm $\times$ 3) because the PET-G film is slightly dissolved with the PET-G solution during the multiple spin coating. The top of the PET-G film is also slightly dissolved with the PMMA solution, and then the interface between the PET-G and the PMMA films is considered to be composed of the mixture of the PET-G and the PMMA. The core width is found to be 46 μm. From the mode



(a)



(b)

Fig. 4. Transmission loss of the PET-G channel waveguide for 660-, 830-, 1310-, and 1550-nm wavelength. (a) $\lambda = 660$ and 830 nm. (b) $\lambda = 1310$ and 1550 nm.

field analysis by the finite difference method, the waveguide support 20 mode at 1550 nm wavelength. The waveguide length was 2 cm or 4 cm.

The propagation loss of the PET-G channel waveguides were estimated by the cut-back method, and the results are shown in Fig. 4. The input light was coupled to the waveguide via a SI-9 optical fiber, meaning that the input fiber is multimoded for 660 nm and 830 nm wavelength and is single-moded for 1310 nm and 1550 nm wavelength. The emerged light from the waveguide was collected by a GI-50 fiber and the transmission loss was measured by an optical power meter. The propagation loss is evaluated to be 0.30 dB/cm, 0.12 dB/cm, 0.35 dB/cm and 0.70 dB/cm for 660 nm, 830 nm, 1310 nm and 1550 nm wavelength, respectively. Regardless of mechanical formation of the core ridge, low propagation loss is achieved. Especially, the propagation loss at 830 nm wavelength is about 0.1 dB/cm, and as a result, the PET-G waveguide can be applicable to optical interconnection utilizing a short wavelength laser source. If a smoother core side wall is achieved by the reactive ion etching or the nano-imprint technology, the propagation loss of less than 0.1 dB/cm may be achieved. The relatively large propagation loss at 1550 nm is due to harmonics of C-H bond vibrational absorption.

IV. Conclusion

We have fabricated polymer optical waveguides made of amorphous PET (PET-G), and the optical properties have been characterized. The PET-G is dissolved in the o-cholorophenol and the PET-G films are fabricated by the spin coating. The refractive index of the PET-G film is 1.5656, 1.5560, 1.5489 and 1.5477 for 633 nm, 830 nm, 1310 nm and 1550 nm wavelength, respectively, and is higher than that of the PFPI and the PMMA. A 12 μm-thick PET-G film was formed on a PFPI/polyimide substrate by the spin coating, and straight optical waveguides with 46 μm-width were fabricated by mechanical grinding using a dicing saw. The propagation loss was measured to be 0.30 dB/cm, 0.12 dB/cm, 0.35 dB/cm and 0.70 dB/cm for 660 nm, 830 nm, 1310 nm and 1550 nm wavelength, respectively. Regardless of mechanical formation of the core ridge, the PET-G waveguides have low propagation loss, which means highly transparent nature of the PET-G films. Lower propagation loss is expected by forming the core ridge by utilizing reactive ion etching or nano-imprint technology. We conclude that the PET-G waveguides can be useful in optical interconnections using a short wavelength laser source.

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