Optical properties of polymer planar waveguides deposited on flexible foils

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In this paper, we present the properties of flexible polymer planar optical waveguides made of EpoCore deposited on Xerox, Melinex, Hostaphan and Plexiglas flexible foil substrates. EpoClad polymer was used as cladding between a foil substrate and the waveguide layer. Waveguide properties were measured by dark mode spectroscopy for five wavelengths (473, 632.8, 964, 1311 and 1552 nm). Propagation optical loss measurements were done by the fibre probe technique at a wavelength of 632.8 nm (He-Ne laser). The best samples had optical losses of about 0.5 dB·cm^{-1}, and the losses generally did not exceed 1 dB·cm^{-1}. Unlike the other structures that have been presented, our construction is fully flexible, which makes it possible to be used in innovative photonic structures.

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1. Introduction

The idea of using planar optical waveguides to replace wired communications for the future interconnections for rack-to-rack, board-to-board, multichip-module communication, etc. has been intensively studied in the last decades [1-3]. The existing interconnection technologies for shorter distances use mainly metal copper wiring connection, but these soon will not be sufficient due to the rising data rates and their sensitivity to electromagnetic interference [4, 5]. Therefore, new optical interconnections are highly desirable.

The replacement of a wired connection by optical signal connections for this purpose may provide many advantages such as a higher bandwidth, immunity from crosstalk and electromagnetic interference, light weight, low skew, jitter and etc. [6, 7].

Despite their being good candidates for common photonics structures, the glass fibres used in conventional optical links or semiconductors and the inorganic crystals and glasses utilised in traditional photonic planar structures and devices are not flexible enough for optical interconnection devices [8, 9].

On the other hand, flexible polymer planar optical waveguides appear to be an excellent choice, because they exhibit a number of attractive optical and mechanical features, such as well-controlled refractive indices, their high transparency from visible to infra-red wavelengths, reasonable temporal and temperature stability. Polymers can also be deposited directly on any kind of flat or curved substrates. Another advantage is their fast and easy fabrication processing, which allows for cost-effective mass production [10-16].

In this paper, we are going to present our research done on EpoCore polymer as a core waveguide material and EpoClad polymer used as cladding both supported by the micro resist technology GmbH. These polymers were chosen for their excellent optical properties (optical losses of 0.25 dB·cm^{-1} at 632.8 nm, 0.2 dB·cm^{-1} at 850 nm, refractive index λ= 830 nm: EpoCore 1.58, EpoClad 1.57) [17, 18] and easy fabrication process. The polymers were deposited onto four different substrate foils, namely Xerox 3R96525 (Xerox Corporation), Melinex® ST726 (DuPont Teijin Films), HOSTAPHAN® GN2504600 (Mitsubishi Polyester Film GmbH), and PLEXIGLAS® Film OF058 (Evonik Industries AG).

2. Planar optical waveguides

Planar waveguides are at the heart of a fundamental element for the realisation of optical ridge or channel waveguides that can be used for the interconnection of various devices of optical integrated circuits and photonic structures. A classic planar waveguide structure consists of a dielectric film of a high refractive index deposited onto a substrate, which is covered with a film of a lower refractive index [19]. The simplest optical waveguide structure is a step-index planar slab waveguide. Since our designed waveguide should be flexible, it is to be deposited onto a thin polymer foil. Refractive indices of common foils for photonic applications have a high value of refractive indices; therefore, it is necessary to insert a suitable cladding layer (n_s) between the substrate and the waveguide layer (n_f). In order to measure waveguiding properties by dark mode spectroscopy, we left the upper side open so that the air would act as a “cover” (n_c). A cross-section view of the design of a flexible planar optical waveguide is illustrated in Fig. 1.

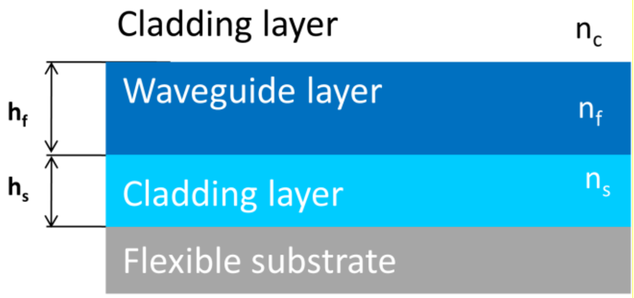

Fig. 1. A schematic cross-section view of the flexible planar optical waveguide.

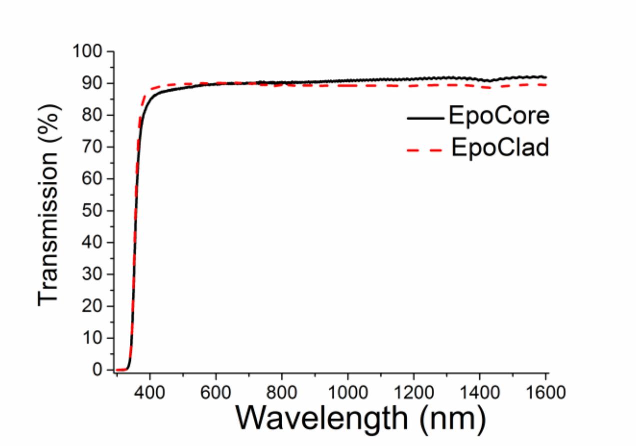

Fig. 2. Transmission spectra of EpoCore and EpoClad polymer deposited onto a glass substrate.

Prior to the practical implementation, we checked the spectroscopic properties of the EpoCore and EpoClad polymers. For that purpose, we deposited the polymers onto (common silicate) glass substrates and collected their transmission spectra by a UV-VIS-NIR Spectrometer (UV-3600 Shimadzu) in the spectral range of 300–1600 nm. The results are given in Fig. 2 and show that the waveguide layers are transparent almost within the range of 400–1600 nm.

As the transmission spectrum measurement has proved that the polymers are suitable candidates for the intended purpose, we proceeded to the implementation of the practical samples. First, the waveguiding properties of the designed samples were considered.

The number of guided modes (*m*) and the thickness (h_f) of the core of the optical waveguides can be determined by solving the modified dispersion equation presented in [13, 14]. The actual design of the optical planar EpoCore-waveguide and the EpoClad-cladding layers was done by using the tabular value of the refractive indices listed in Table 1 [17]. The refractive indices of the thin foils were measured by dark mode spectroscopy. The result is also given in Table 1.

Table 1. The refractive indices used for the design of the flexible planar waveguides. The values of the refractive indices of substrate foils were measured by dark mode spectroscopy. The refractive indices of the EpoClad-cladding and EpoCore-waveguide layers are tabular values obtained from [17].

λ	**n (-)**					
(nm)	Xerox	Melinex	Hostaphan	Plexiglas	EpoClad	EpoCore
473	1.701	1.698	1.672	1.499	1.610	1.620
633	1.671	1.668	1.645	1.489	1.590	1.599
964	1.652	1.649	1.628	1.483	1.577	1.584
1311	1.645	1.642	1.622	1.479	1.572	1.579
1552	1.642	1.639	1.619	1.478	1.570	1.577

As the design was intended for the standard multimode optical fibre 50/125 μm, it was convenient to work with a 50-μm-thick planar waveguide layer. The results of the TE-mode calculations performed for wavelengths of 632.8 nm, 964 nm, 1311 nm and 1552 nm (for the waveguiding layer that was 50 μm thick) showed that the waveguides supported the following number of modes: 27 modes at 632.8 nm, 15 modes at 964 nm, 11 modes at 1311 nm and, finally, 10 modes at 1552 nm.

3. Fabrication

The experiments were performed on four types of foil substrates: Xerox 3R96525 (a thickness of 100 μm), Melinex® ST726 (a thickness of 175 μm), Hostaphan GN2504600 (a thickness of 250 μm) and PLEXIGLAS® Film OF058 (a thickness of 200 μm). The claddings were made of EpoClad polymer and the cores of the waveguides were made of Negative Tone Photoresist EpoCore polymer (supplied by the Micro Resist Technology GmbH). The fabrication process of the planar polymer flexible waveguides is illustrated step by step in Fig. 3.

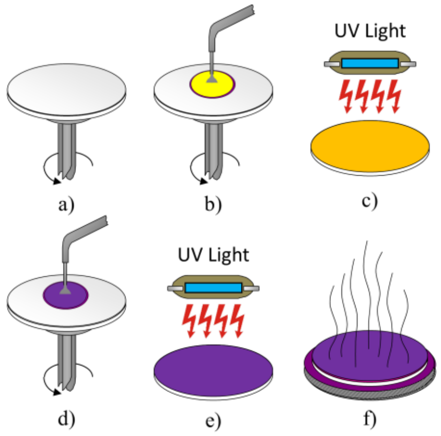

Fig. 3. The fabrication process for EpoCore planar optical waveguides: a) substrate cleaning, b) the deposition of an EpoClad-cladding layer, c) the EpoClad UV-curing process, d) the deposition of an EpoCore-waveguide layer, e) the EpoCore UV-curing process, g) hard baking.

The first step was a standard cleaning procedure followed by the deposition of a primer (MCC Primer 80/20 – MicroChem P021020) to improve adhesion (Fig. 3a). Subsequently, EpoClad-cladding layers were deposited on the substrate by spin coating (Fig. 3b), after which the soft-bake process was applied on a hotplate at 50°C for 10 min. Then the temperature was gradually increased to 80°C (at 10°C/min). After that, a UV-curing process was applied followed by a bake process (Fig. 3c). The next step was the deposition of an EpoCore layer on it by spin coating (Fig. 3d) and again, the soft-bake process was applied on a hotplate at 50°C for 10 min. Afterwards, the temperature was once again gradually increased to 80°C (at 10°C/min). This was again followed by the UV-curing process (Fig. 3e). Next, the post-exposure bake was done on a hotplate at 50°C for 10 min. The last step was to increase gradually the temperature (at 10°C/min) again to 80°C. Finally, hard baking was applied (Fig. 3f).

The above described process was used for deposition onto all but one substrate, which was PLEXIGLAS® Film OF058. In the case of this foil, we did not need to deposit any cladding layer, because PLEXIGLAS® Film OF058 has a low refractive index value (1.4893 at 632.8 nm). It means that the steps 3b and c were omitted.

4. Results

The thicknesses of the fabricated polymer layers were measured by Talystep Hommel Tester 1000 profile metres. The experimentally found thicknesses of the cladding and core waveguide layers ranged from 10 up to 70 µm depending on the rate of spinning of the coater during the deposition.

The waveguiding properties of the flexible EpoCore planar waveguides were examined by dark mode spectroscopy using the Metricon 2010 prism-coupler system [20]. Prism coupler was originally demonstrated by P.K. Tien and R. Ulrich [21, 22]. The prism-coupling technique utilised the process of measuring the effective indices of the propagation modes, which can be obtained by measuring the coupling angles. A schematic view of the prism dark mode spectroscopy setup is shown in Fig. 4.

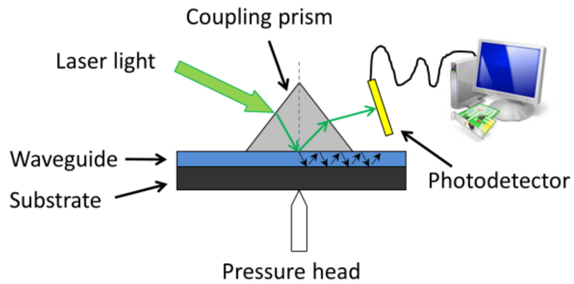

Fig. 4. A schematic view of the dark mode spectroscopy measurement.

The waveguiding properties were measured at five wavelengths (473, 632.8, 964, 1311 and 1552 nm). Fig. 5a gives an example of the mode spectra measured for 632.8 nm of the multimode EpoCore/EpoClad planar waveguide deposited on a Melinex ST726 foil substrate (the mode spectra of the remaining two waveguides deposited onto Xerox 3R96525 and Hostaphan GN2504600 foils are very similar), whereas Fig. 5b provides an example of the measured mode spectra of the multimode EpoCore planar waveguide deposited on a OF058 foil substrate.

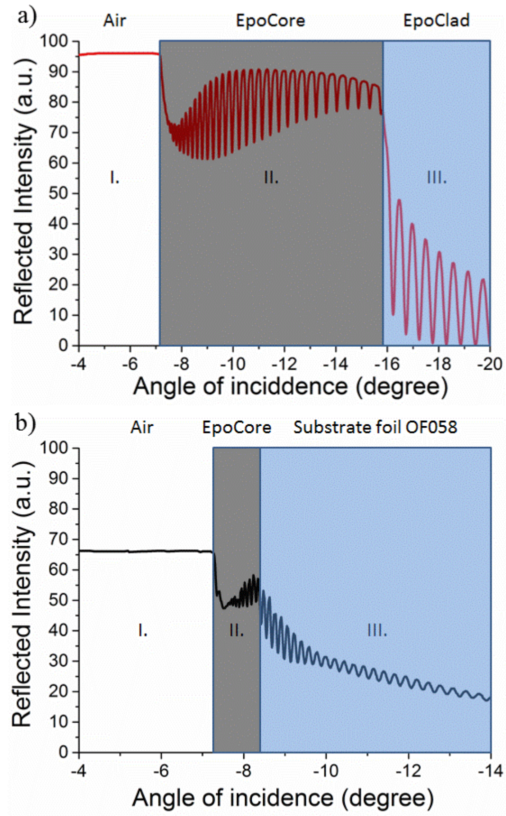

Fig. 5. The TE mode pattern for a wavelength of 632.8 nm: a) EpoCore/EpoClad planar waveguides deposited on Melinex ST726 foil substrate, representing also the Xerox 3R96525 and Hostaphan GN2504600 foils; b) EpoCore planar waveguides on an OF058 foil substrate.

Area I in Fig. 5a corresponds to an air-cover layer and area II corresponds to an EpoCore-waveguide layer. According to the calculations, area II might have shown at 632.8 nm 27 modes; however, it is too narrow to have all these modes clearly pronounced, so that they blend with each other. Area III represents an EpoClad-cladding layer. The substrate areas are not visible. From the incident angle value, one can determine the refractive index value. Here we used the surface incident angle value and the core-layer incident angle value from the interface between areas I and II to obtain the pertinent refractive index values for the EpoCore-waveguide layer. The surface incident angle value between II and III provided the refractive index for the EpoClad layer. Area I in Fig. 5b corresponds to the air-cover layer and area II corresponds to the EpoCore waveguide like in Fig. 5b, but here area III refers to the OF058-foil substrate. The obtained values of refractive indices are summarised in Table 2 for all five wavelengths. The table shows that the deposited layers were waveguiding at all the five wavelengths used. It also illustrates a decrease of the refractive index values with the increasing wavelengths of the measurement.

Table 2. The evaluation of the refractive indices for the EpoClad-cladding and EpoCore-waveguide layers by dark mode spectroscopy.

λ (nm)	**n (-)**			
	Xerox		Melinex	
	EpoClad n_c	EpoCore n_f	EpoClad n_c	EpoCore n_f
473	1.599	1.607	1.604	1.607
633	1.578	1.586	1.582	1.586
964	1.567	1.574	1.570	1.574
1311	1.561	1.569	1.564	1.569
1552	1.561	1.566	1.560	1.566

λ (nm)	**n (-)**		
	Hostaphan		PLEXIGLAS
	EpoClad n_c	EpoCore n_f	EpoCore n_f
473	1.582	1.610	1.614
633	1.572	1.590	1.594
964	1.569	1.574	1.579
1311	1.564	1.568	1.575
1552	1.562	1.565	1.572

The optical attenuation of the optical planar waveguides prepared was evaluated from the measurements of the scattered intensity as a function of the propagation distance. The method of fibre scanning was used for this purpose. In the method, an optical fibre is scanned along the film to collect the scattered light, which is then read by a photodetector [12]. The light (He-Ne laser at 632.8 nm) was coupled into the planar waveguides through an optical coupling prism and the outgoing scattered light intensity was detected by an optical fibre connected to a Si detector. The principle of the method is shown in Fig. 6.

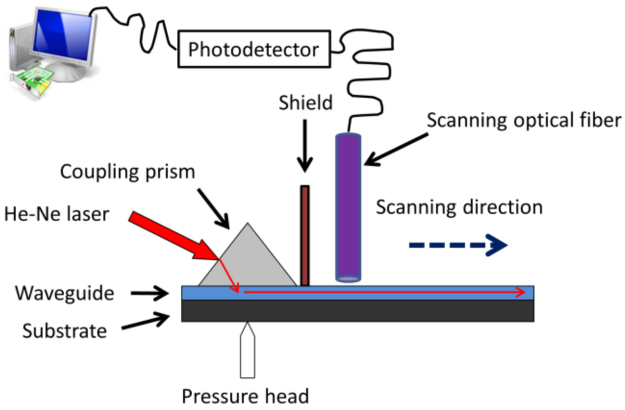

Fig. 6. A schematic view of the optical planar loss measurement.

Fig. 7 shows an image of planar waveguides supporting light at 632.8 nm. Since the substrate was very thin (up to 300 µm) in this case, it had to be underlaid with a pad of glass to achieve optical contact. A shield prevented a reflection of the light, which would have otherwise affected the measurement (the coupling prism is not visible in the picture, it is under the shield).

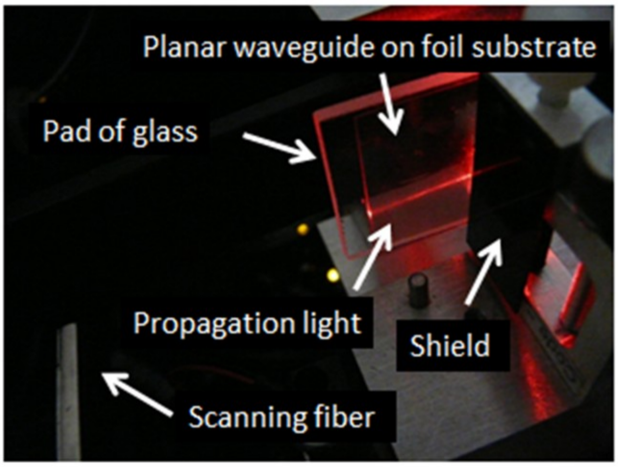

Fig. 7. Propagation of the optical light (632.8 nm) through the planar EpoCore waveguides deposited onto a thin foil (in this particular case the Xerox 3R96525 foil) substrate for optical loss measurements.

The results of the optical loss measurements are demonstrated in Fig. 8 and in Fig. 9. The results for an EpoCore/EpoClad planar waveguide on a Xerox 3R96525 substrate are shown in Fig. 8a and the results for an EpoCore/EpoClad waveguide on a Melinex ST726 substrate are shown in Fig. 8b.

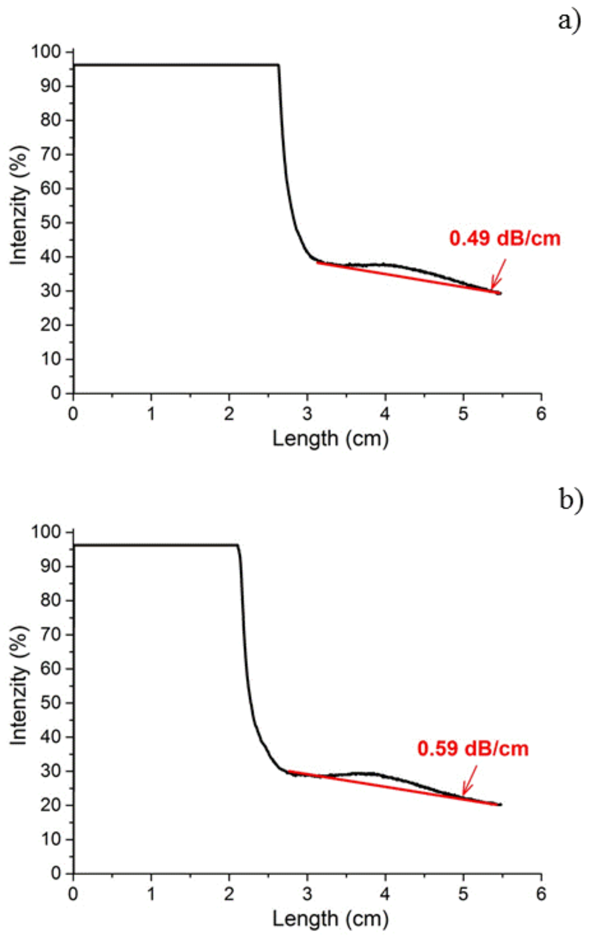

Fig. 8. Optical losses of the flexible EpoCore planar waveguides for a wavelength of 632.8 nm on a) an EpoClad/Xerox 3R96525 foil, b) an EpoClad/Melinex ST726 foil.

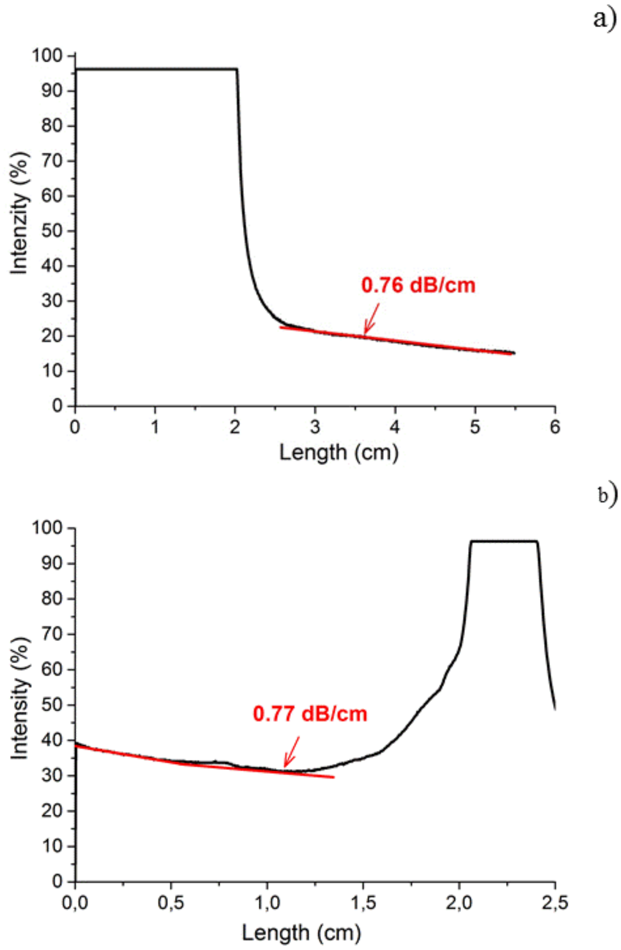

Fig. 9. Optical losses of the flexible EpoCore planar waveguides for a wavelength of 632.8 nm on a) an EpoClad/Hostaphan GN2504600 foil, b) a PLEXIGLAS OF058 foil.

The results of the optical loss measurements for an EpoCore/EpoClad waveguide on a Hostaphan GN2504600 substrate are shown in Fig. 9a, and finally the results for an EpoCore waveguide on a PLEXIGLAS OF058 substrate are shown in Fig. 9b. The values of optical losses were determined for the stabilised optical field, which occurred within 2.5–5.5 cm.

Our optical planar waveguides had optical losses below 0.8 dB·cm^{-1}, with the best sample having optical losses as low as 0.5 dB·cm^{-1}.

5. Conclusion

The paper report on the design, fabrication and properties of flexible polymer planar optical waveguides deposited on foil substrates. EpoCore polymer was used as an optical planar waveguide deposited on EpoClad polymer used as a cladding layer, whereas Xerox, Melinex, Hostaphan and Plexiglas foils were used as substrates. The waveguiding properties of the planar waveguides were characterised by the Metricon 2010 prism-coupler system for five wavelengths (473, 632.8, 964, 1311 and 1552 nm) and optical losses were measured by collecting the scattered light using fibre scanning along the waveguide read by the Si photodetector at 632.8 nm. Our best sample had optical losses around 0.49 dB·cm^{-1}.

The main advantage of our samples is that they are deposited on flexible substrates, which makes them suitable for advanced sophisticated interconnection devices. Next, we are going to design and construct multimode flexible ridge waveguides based on the same principle.

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