Study of Optical Losses in Poly(3-octylthiophene) Planar and Inverted RIB Waveguides

Khalida Messaad, Joël Charrier, Alexandra Mosqueron, Dominique Bosc, Philippe Rochard

Université européenne de Bretagne (UeB) CNRS, FOTON, UMR 6082, CCLO, ENSSAT BP 80518, 22305 Lannion cedex, France

Received 19 May 2010; accepted 17 October 2010
DOI 10.1002/app.33943
Published online 16 March 2011 in Wiley Online Library (wileyonlinelibrary.com).

ABSTRACT: Poly(3-octylthiophene), (P3OT) in addition to its electronics properties exhibits a high Kerr coefficient, n_2, due to its third order nonlinear dielectric susceptibility. At the wavelength of 1550 nm, this coefficient n_2 is one of the highest. So, this material should be suitable to build integrated all optical switching devices. To construct this device, it is necessary to make a single-mode optical waveguide. For the time being, such a P3OT waveguide has never been obtained due to excessive optical losses. In view to produce single-mode waveguide with P3OT as a core, we investigated the different causes of these optical losses in the material and in the guiding structure. We characterized the optical transmission at key steps in its development. First, we demonstrated that the intrinsic polymer absorption is not a limiting factor at 1550 nm, and then we studied the transmission properties of planar (1-D confined light) and channel waveguides (2-D confined light). The results revealed that better transmission properties can be achieved using planar waveguides rather that confined channel waveguides. This article describes the development and the characterization of the guiding structures that enabled us to identify the main origins of optical losses. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 121: 2134–2142, 2011

Key words: optics; nonlinear polymers; conducting polymers; films; light scattering

INTRODUCTION

Some conjugated polymers (CP) are known to exhibit strong Kerr coefficient, n_2, due to important nonlinearities which have an ultra fast response time (inferior to ps). As their n_2 can be four orders of magnitude greater than the one of the silica.[1] So, we had to develop waveguides to enable optical signal processing. However, to our knowledge, there are very few articles on acceptable optical propagation, in based-CP waveguides.[2] We selected the poly(3-alkylthiophene) class (P3AT), because it offers better solubility and filmability and moreover they can be easily synthesized. So far, with regards to this material, it can be noted that any propagating waveguides have not yet been reported. Moreover, P3AT is included in a class of polymers which exhibits a bulk Kerr coefficient n_2 around $10{,}000 \times 10^{-16}$ cm^2 W^{-1}, whereas this coefficient is less than 1000×10^{-16} cm^2 W^{-1} for chalcogenide and is in the order of 3×10^{-16} cm^2 W^{-1} for silica.[3] These high performances allow the manufacture of very small size devices for all optical signal processing. However, for this purpose, single-mode waveguides should be developed. This means that the light is confined in a 2-D channel waveguide where the guide core size is limited to few square micrometer depending on the index contrast between core and cladding materials. This will be explained further on in this article. The P3OT is one of the most soluble CPs, which exhibits good solubility and which makes it possible to spin-coat films. For these reasons and its high n_2, we have chosen to study the waveguide development using P3OT. Recently,[4] we have reported the first results that we obtained with ridge and strip loaded single-mode waveguides based on P3OT as guiding layer. Unfortunately, no light propagation was observed. In this article, we present the investigations that we undertook to achieve a better understanding of the loss sources.

Generally, the mechanisms of losses are mainly due to (i) absorption of the material, (ii) surface scattering due to interface roughness, (iii) volume scattering due to nanoscale refractive index modulation (defaults in bulk material), and (iv) radiative modes. The scattering losses can be considered as a critical parameter since scattering centers in the material or the guide can hinder the propagation because the size of scattering centers is over $\lambda/100$.

After examining the intrinsic absorption of the 3-octyl thiophene molecule, we report qualitative and quantitative measurements of the propagation losses obtained in both planar (film) waveguides and

Correspondence to: D. Bosc (dbosc@enssat.fr).

Journal of Applied Polymer Science, Vol. 121, 2134–2142 (2011)

channel (inverted rib) guiding structures for two wavelengths (1330 and 1550 nm). The study of these three configurations, bulk material, film and rib, enable us to reflect on the different loss factors. To determine the different contributions of losses due to volume and surface scattering, material absorption and radiative modes, these experimental measurements were compared with expected theoretical performances. Finally, the different mechanisms responsible for the optical losses in particular for planar waveguides were considered. For optic integrated devices, some inverted rib structures were formed based on P3OT core and were characterized by measuring optical transmission.

EXPERIMENTAL CONDITIONS

Synthesis of polymer material

Due to the facility of synthesis, we choose to synthesize regio-irregular P3OT (RIRg). P3OT RIRg possesses lower NLO (nonlinear optical) properties (around five times less) than those of P3OT regioregular (RRg). However, its properties are much better than those of minerals.[5] The most commonly used method is the $FeCl_3$ method (Fig. 1) where the monomer 3OT is oxidatively polymerized by $FeCl_3$ in anhydrous chloroform. The experimental process to prepare a P3OT polymer is as follows. A mixture of $FeCl_3$ and dry chloroform is mixed together under nitrogen. The monomer, 3OT, is added dropwise to the mixture over a period of 10 min, the mixture is stirred for 7 h, and then the solution is washed to extract the polymer. During different syntheses, some chemical reaction conditions, such as the period of monomer drop addition, the way of extracting polymer, and the period of reaction, have been changed to improve the yield (up to 90%) and the polymer solubility and consequently its processability. Thereby, we have been able to synthesize P3OT with high solubility (150 g/L in $CHCl_3$ or in toluene). The ratio of Fe impurities in the polymer can be as low as 110 ppm instead of superior to 1000 ppm before synthesis. A small content of Fe avoids some optical losses due to scattering.

We obtain soluble P3OT and we measure the average molecular weights by the size-exclusion chromatography (SEC) technique. The measurements were conducted in the Central Laboratory of CNRS with a VARIAN machine. The synthesized polymer was

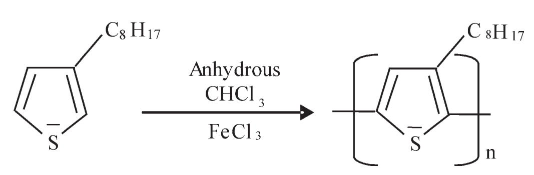

Figure 1 Chemical synthesis scheme of P3OT.

dissolved in tetrahydrofuran solvent, THF, and the calibration curve was created using known molecular weight (polystyrene) having columns with standard polystyrene (200–350,000 g $mole^{-1}$). Molecular weight (Mw) and molecular number (Mn) are 122,000 Dalton and 41,000 Dalton, respectively. With these relatively high Mw values, we could also expect that synthesized material has good mechanical properties.

Planar and inverted rib waveguides processing (photolithography and dry etching methods)

To study the loss factors, we first decided to examine the absorption losses of 3-octylthiophene molecule, then the losses in the bulk state. To achieve this, we examined the transmission of planar waveguides and channel waveguides (with an inverted rib configuration). In comparison with planar waveguides where the propagation is along the y direction, the mode propagation in the channel waveguide is along both the x and y directions. So, the losses due to interface roughness are minimized in the case of planar waveguides.

A planar waveguide is made by deposing the optical nonlinear polymer as a core layer, onto an optical cladding with an index less than the index of the polymer core.

The experimental procedure used to produce planar waveguide is as follows. Under clean room conditions, first, out of a poly(methyl methacrylate) (PMMA) solution (250 g/L filtered at 0.2 μm deposited at 2000 rd/mn), a 4.5-μm thick PMMA film ($n = 1.48$ at 1550 nm) is spin-coated onto a cleaned 12-μm thickness of silica substrate (on a 3 in. Si wafer). The film is heated to 110°C for 15 min to evaporate the residual solvent (1,1,2 trichloroethane [TCE]). Then, a thin layer of silica (~ 20 nm of thickness) is sputtered on the top of the PMMA film, which forms the barrier layer. Finally, from a P3OT solution (150 g/L in toluene at 2000 rd/min), a P3OT film is deposited to form a 2.5-μm thick film. This structure acts as a planar waveguide along the vertical axis.

After measurement of optical losses in planar waveguides, an inverted rib waveguide was developed to make channel waveguide structures without having to etch the P3OT. So far, we have shown that due to the poor mechanical properties of this polymer,[3] P3OT etching can not be used, for example to form a ridge waveguide. An inverted rib waveguide is made in two stages: first, a slit trench waveguides is made using a buffer polymer by standard photolithography and RIE techniques and second, the slit trench waveguide is filled with P3OT nonlinear polymer by spin-coating. The PMMI (poly-methymethacrylateimidized) buffer was chosen because it has an index of 1.52 at 1550 nm and at 20°C. The slit

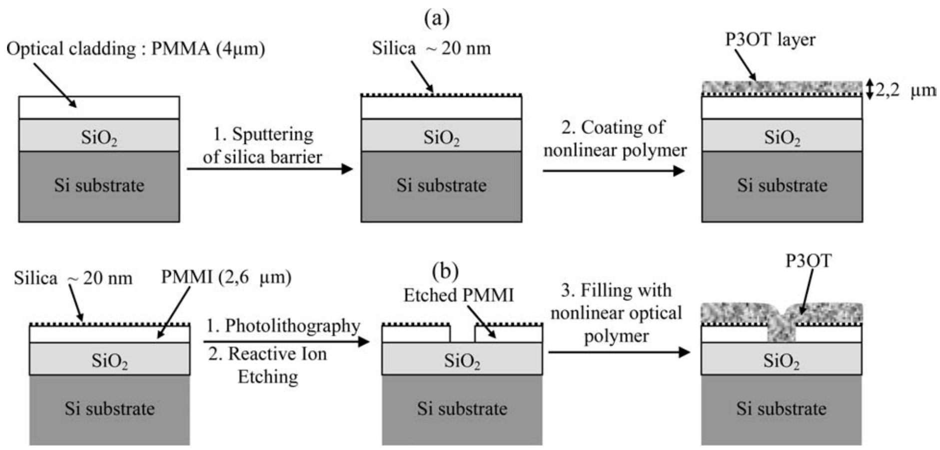

Figure 2 Schematic steps to elaborate (a) planar waveguide and (b) rib inverted waveguide.

trench waveguide is fabricated by a dry etching process using RIE equipment. The schematic steps to create planar and inverted rib waveguides are illustrated, respectively, in Figure 2(a,b).

Optical experimental set-ups

The effective refractive indices of the propagation modes in the planar waveguide were measured by the *m*-lines method, with a Metricon-2010 instrument. A laser beam at wavelengths 1302 and 1540 nm were directed through a Rutile prism into the P3OT film. From these measurements, the refractive indices and the thicknesses were accurately deduced in the order of 10^{-4}. This method was used to measure the thickness because the cleavage of faces is of bad quality so the cross section scanning electron microscopy (SEM) images are not clear enough to precisely measure the layer thickness (Fig. 3).

The absorbance and reflectance spectra of the material were studied by a LAMBDA 900 Perkin–Elmer beam spectrometer equipped with a specular reflectance module with a 6° fixed angle for reflectance spectra.

Moreover, optical losses were measured using two different methods avoiding the injection of light by the cross section, because the cleavage of faces presented many defects. The first method (Fig. 4a) consisted of directing the optical beam by prism coupling into a planar waveguide manufactured from a P3OT film deposited on a PMMA film which had a lower refractive index than the P3OT one. A detector was placed at the end of the wafer to collect light from the planar waveguide. Waveguide linear

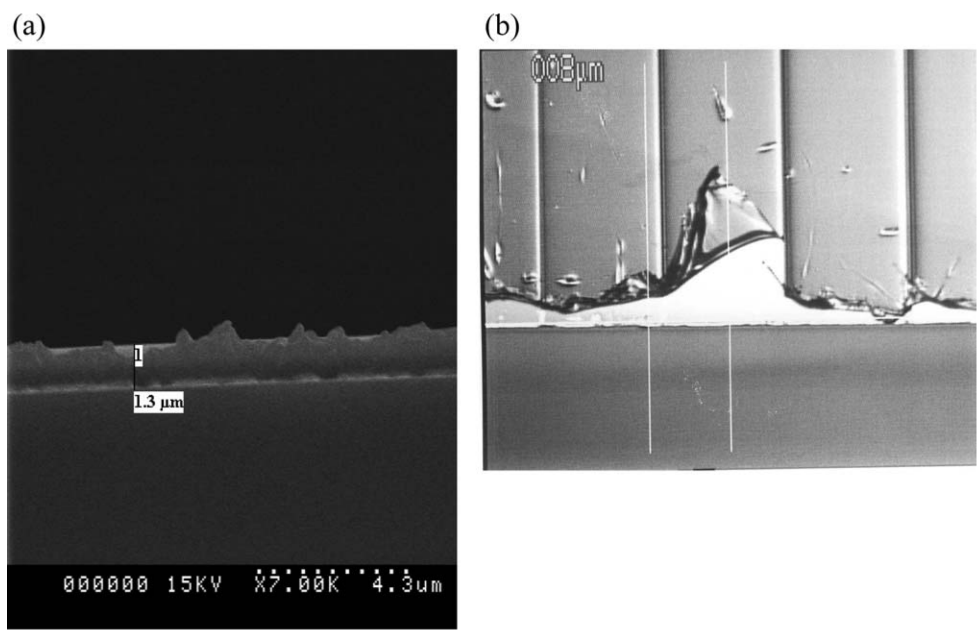

Figure 3 Micrographs of (a) cross section of planar waveguides and (b) top-view of inverted rib waveguides obtained by SEM.

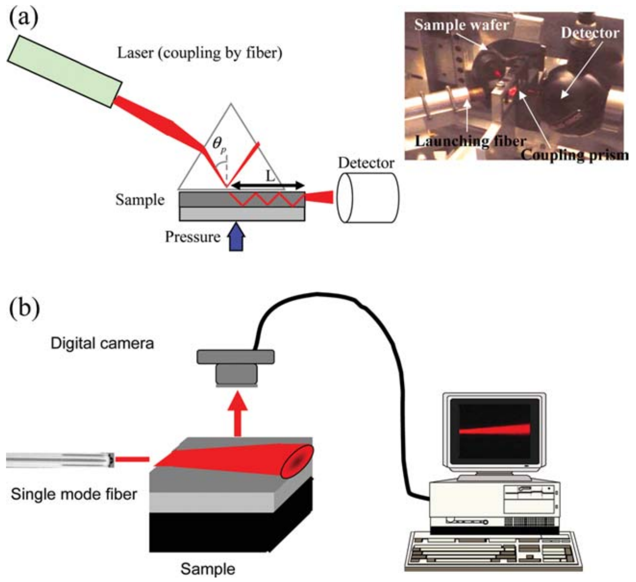

Figure 4 (a). Scheme and picture of the set-up of prism coupling measurements (b) Scheme of optical loss measurement by studying the scattered light from the surface of the waveguide. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

losses are usually expressed by dB cm^{-1} and calculated from the formula $\alpha(\text{dB cm}^{-1}) = (10/L) \times [\log_{10}(I_i/I_t)]$ where I_i is the incident intensity directed into the waveguide and I_t, the transmitted intensity through a waveguide length, L. For coupling to occur, it is necessary that the components of the phase velocities of the waves in z direction are the same in both the waveguide and the beam. These conditions were achieved for several coupling angles corresponding to the transmission modes of the planar waveguides. For each length L by moving the coupling prism after each measurement, the light intensity at the output of waveguide was measured. So the loss coefficient can be determined from the slope of the collected light intensity as a function of the length L. To have the best precision, the output detector should be positioned and masked so that is collecting only the light emerging from the waveguide.

Second, the optical losses were measured by studying the scattered light from the surface of the waveguide.[6,7,8] Laser light was single-mode fiber butt-coupled to the waveguide (Fig. 4b). The intensity of the scattered light was recorded with a digital camera placed above the sample. Transverse scanning along the light propagation direction enabled the 2-D light intensity distribution of the waveguide modes to be obtained. The longitudinal variation was obtained by integrating the data along each sampling transverse line. The area covered by the transverse scanning with the digital camera is the width of the sample. The light intensity decreased exponentially with the z-propagation distance. In this study, the attenuation values were the average of several measurements performed on several samples. The polarization of the coupled light in the waveguide was not controlled.

In addition, light propagation was observed at the output of the waveguides by near field profiles of guided modes at 1550 nm.

RESULTS AND DISCUSSION

Characterization of the planar waveguides

The refractive indices of PMMA and P3OT films were measured by *m*-line method at 1330 and 1550 nm. This method is based on the principle of distributed coupling through evanescent fields to the modes of thin film waveguides. By using the dispersion equation, we determined the refractive indexes of the wave guiding and cladding layers and the thickness of the guiding layer. The refractive index values were accurately evaluated (error <0.001). Figure 5a shows the angular spectrum obtained by the *m*-line method applied to three material layers where we can observe the dips of mode coupling, two in the P3OT layer, one in the PMMA layer underneath and several modes in the silica substrate. From this spectrum, the index values of the different layers are extracted. The index profile as a function of the thickness of the films is represented in Figure 5b. These index values of the involved polymers are shown in Table I. Taking these indexes into account, we calculated the effective index of the propagated mode. Thus, the propagated modes were calculated using the dispersion equation for a planar waveguide composed by a P3OT guiding layer and a

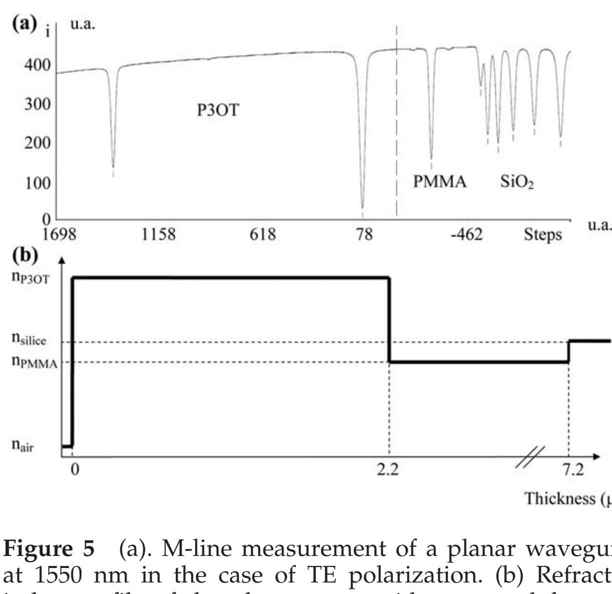

Figure 5 (a). M-line measurement of a planar waveguide at 1550 nm in the case of TE polarization. (b) Refractive index profile of the planar waveguide extracted from the simulation.

TABLE I
Refractive Indices of Layers at 1330 and 1550 nm Measured by m-Lines Method

Name of the layer	Index at 633 nm	Index at 1330 nm	Index at 1550 nm
PMMA	1.495	1.483	1.481
P3OT	Not transparent	1.63	1.62

PMMA cladding layer as a function of the thickness of the guiding layer (Fig. 6). This figure provides the thickness values linked to the effective index demarcating the thickness where a single mode can be propagated and the thickness where several mode (multimode regime) can propagate in the channel waveguide. The effective refractive index values are presented in Table II and show good correlation with the *m*-line measurement of the manufactured planar waveguide at 1550 nm as shown in Figure 6 for a guiding layer thickness equal to 2.2 μm.

Then, the losses at 1330 and 1550 nm were measured on the planar waveguides by two methods: prism coupling and scattered light from the surface of the waveguide. By prism coupling, the optical losses associated to each mode were measured separately, whereas when the scattered light was used,

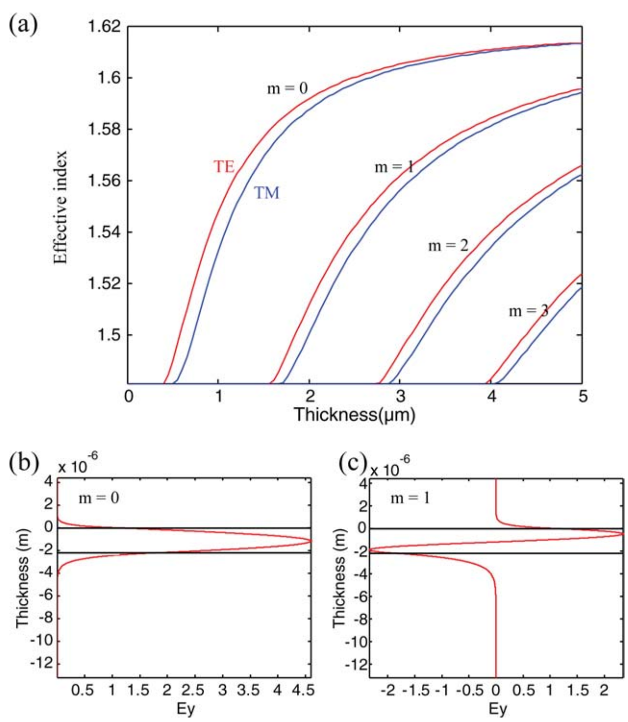

Figure 6 (a). Effective index as a function of the thickness for planar waveguide. Field profile for $m = 0$ (b) and $m = 1$ (c) in the case the TE polarization. $t = 0$ corresponds to the interface air/guiding layer and $t = -2.2 \times 10^{-6}$ m corresponds to the interface guiding layer/cladding layer. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE II
Effective Refractive Indices at 1550 nm

Mode number	Effective index at 1550 nm
$m = 0$	1.596
$m = 1$	1.526

the measured optical losses were attributed to the whole guided modes. The measured attenuation coefficient mainly depends on: (i) material absorption (α_{abs}), (ii) surface scattering (α_{surf}), due to interface roughness and (iii) volume scattering (α_{vol}), due to the inhomogeneity of the refractive index and (iv) radiative losses (α_{rad}). Thus, the overall attenuation is equal to the sum of all these optical loss contributions. The measured values are shown in Table III at 1330 and 1550 nm. The optical losses measured by these two methods are of the same order of magnitude. Fig. 7a, b show the measured light intensity at the output of the waveguide as a function of the waveguide length at 1330 and 1550 nm for the first mode. For the two guided modes, the optical loss values are nearly equal. A good correlation is observed in the two cases on the measured point alignment. Figure 7c, d present the top-view image of the light scattered along the wavelength at 1550 and this scattered light intensity as a function of the waveguide length obtained by the picture analysis. From the exponential decay fit, the value of attenuation is deduced. So, with these two methods, the optical losses are always higher at 1330 nm than those at 1550 nm. This result could seem surprising because the material absorption is lower at 1330 nm than at 1550 nm.

Theoretical optical losses on planar waveguides and discussion

Four reasons have already been evoked to explain the origin of optical losses: (i) absorption, (ii) volume scattering and (iii) surface scattering, and (iv) radiative modes. The different loss factors were calculated to compare these with the experimental results.

i. An idea of the absorption spectrum of the material can be easily obtained by studying the

TABLE III
Measured Values of Optical Losses as a Function of the Wavelength for Planar and Inverted Rib Waveguides

Type of waveguides	Losses at 1330 nm (dB/cm)	Losses at 1550 nm (dB/cm)
Planar waveguides (1)	2.4	1.8
Planar waveguides (2)	2.9 ± 0.6	1.9 ± 0.6
Inverted rib waveguides (2)	3.2 ± 0.6	2.3 ± 0.6

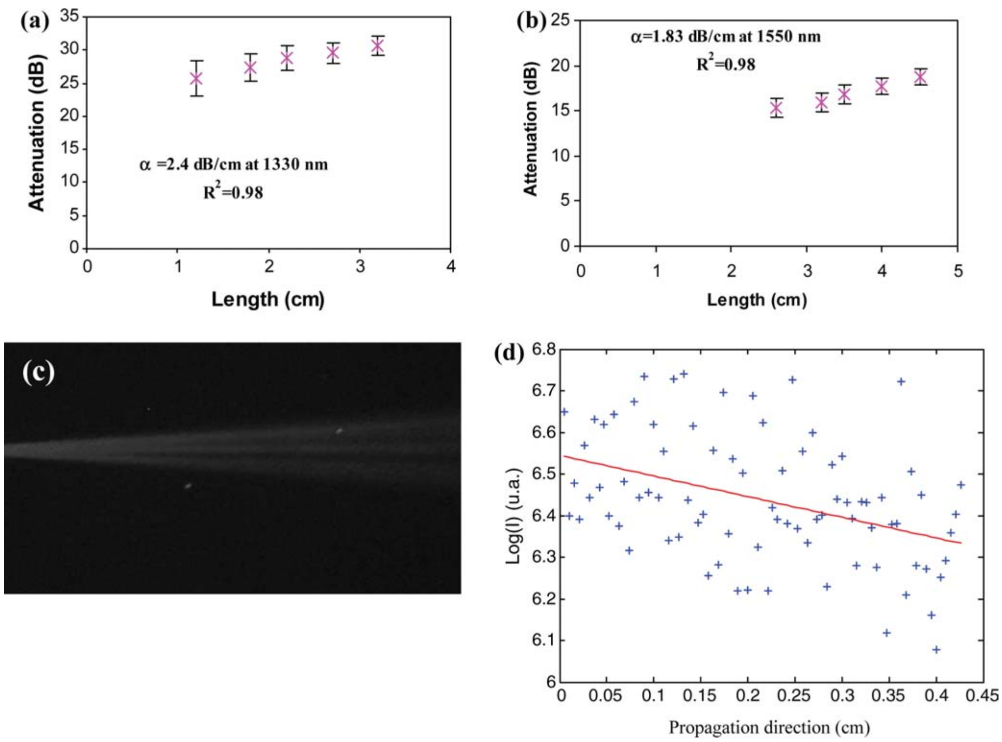

Figure 7 Optical intensity measurement as a function of the planar waveguide length at 1330 and 1550 nm by prism coupling (a) and (b), respectively. Light propagating in the planar waveguide at 1550 nm (c). Logarithmic of light intensity (*I*) propagating in the planar waveguide as a function of the propagation distance at 1550 nm (d). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

absorbance of monomer. The monomer 3OT and the unit of the polymer P3OT are chemically similar. The intrinsic absorption band of the monomer 3OT can be analyzed by spectroscopy from a pure monomer long path cell instead of polymer in a solvent. By using different cell lengths filled with 0.2-μm filtered 3OT liquid the absorbance spectra shows three kinds of absorption bands mainly due to the overtone of C—H bound (Fig. 8). Containing aromatic and aliphatic groups, in 3OT monomer, the fundamental vibration due to stretching C—H bound occurs at around 3240 nm. From the spectra, the second overtone vibration is observed around 1640 nm, the third harmonic around 1200 nm and we can also observe an intermediate broad-band around 1400 nm which is a combination band due to several modes of vibrations. From these measurements, we can determine the optical losses of the 3OT monomer in the range of 0.6 dB/cm at 1550 nm and 0.3 dB/cm at 1320 nm, which is of the same order of magnitude as PMMA bulk material attenuation. Inside these two transmission windows, the level of optical losses concerns part of the intrinsic C—H band tails and part of the extrinsic scattering due to insoluble particles sized less than 0.2 μm. So the value of losses due to absorption has been estimated at 0.6 dB/cm at 1550 nm and 0.3 dB/cm at 1320 nm.

ii. (ii) In our case, the material seems homogeneous and dense. The refractive index was considered as constant in depth. The solution was filtered and all insoluble particles smaller than 0.2 μm can pass through the filter. Propagation losses of the waveguide could occur from light

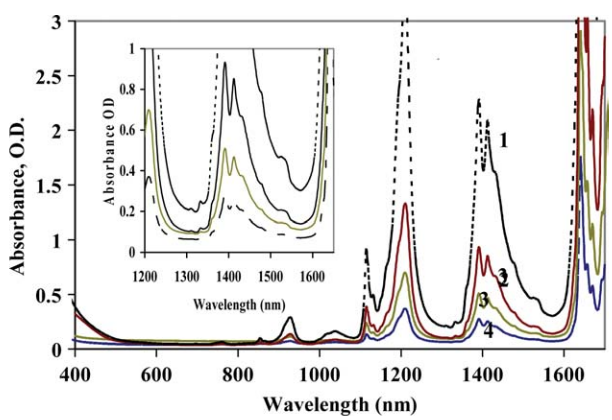

Figure 8 Absorbance spectra of pure filtered monomer cells with different optical path (1: 5 cm, 2 : 2 cm, 3 : 1 cm, 4 : 0.5 cm). The inset gives details in the 1200 nm to 1600 nm wavelength range. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

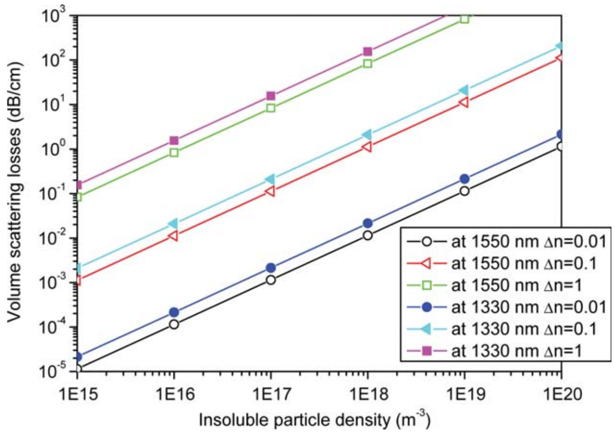

Figure 9 Volume optical losses as a function of the insoluble particle density at 1330 and 1550 nm at 1330 and 1550 nm for different refractive index differences Δn. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

volume scattering due to the inhomogeneous nature of the guiding layer [insoluble particles with a radius a of a few hundred nanometers (in our case $a = 200$ nm)]. These losses can be calculated from Mie scattering loss contribution.[9] In this model, the losses depend on the insoluble particle density N, the refractive index of the guiding layer (P3OT), the used wavelength λ, and the ratio m of the refractive index between P3OT and insoluble particles. The volume attenuation is given by the following formula:

$$\alpha_{\text{vol}} = \frac{8\pi}{3} N \left(\frac{2\pi n_{\text{P3OT}}}{\lambda}\right)^4 a^6 \left(\frac{m^2-1}{m^2+2}\right)^2$$

Figure 9 represents volume losses calculated as a function of density N multiplied by $(m^2 - 1)^2/(m^2 + 2)^2$ in the case of planar waveguide at 1330 and 1550 nm. The volume losses in Figure 9 greatly increase with the ratio N whatever the used wavelength. Moreover, for a fixed value of N, losses decrease with wavelength. The particles can be a principal source of losses if the density becomes important. For example, at 1330 nm and for a refractive index difference between P3OT and insoluble particles $\Delta n = 0.1$, the volume optical losses increase from 0.002 dB/cm to 100 dB/cm when the insoluble particle density varies from 10^{15} to 10^{20} m^{-3}.

iii. Surface scattering losses are related to the root mean square (rms) deviation of the planarity at guiding layer interfaces (σ). Light intensity lost by surface scattering at the two interfaces of the guiding layer is given by the model developed by P. K. Tien[10] according the following equation:

$$\alpha_{\text{surf}} = \left(\frac{4\pi}{\lambda}\right)^2 \left(\sigma_{12}^2 + \sigma_{01}^2\right) \left(\frac{\cos^3\theta}{2\sin\theta}\right) \times \left(\frac{1}{t + 1/p_{10} + 1/p_{12}}\right)$$

where t is the thickness of the guiding layer, $1/p_{10}$ and $1/p_{12}$ are lateral penetration depths of the ray, respectively, in the air and in the cladding layer. θ is the angle between the light path and the normal of the interfaces in the cladding, guiding layers and air, λ is the used wavelength. σ_{01} and σ_{12} represent, respectively, the roughness at the interface air/guiding layer and at the interface guiding layer/cladding layer.

In this model, we assume that the roughness values σ_{01} and σ_{12} are the same. Figure 10 represents surface losses calculated as a function of roughness (σ), for the two first modes (from $m = 0$ and to $m = 1$), in the case of a planar waveguide at 1330 and 1550 nm. The surface losses in Figure 10 greatly increase with both the value of σ and with the mode order. Moreover, for a fixed value of σ and for the same mode, losses increase slightly with wavelength. The loss values can become very important as a function of the value of the roughness and can be a principal source of losses. For example for the fundamental mode at 1550 nm, the surface optical losses increase from 0.3 dB/cm to 27 dB/cm when the roughness varies from 10 to 100 nm.

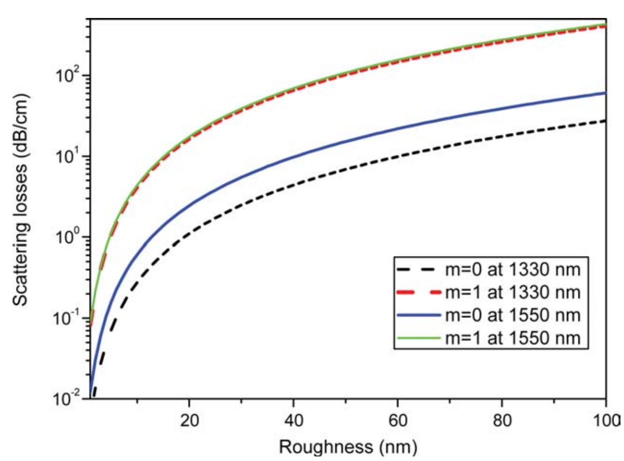

Figure 10 Scattering optical losses as a function of the roughness for $m = 0$ and $m = 1$ at 1330 and 1550 nm in the case the TE polarization. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

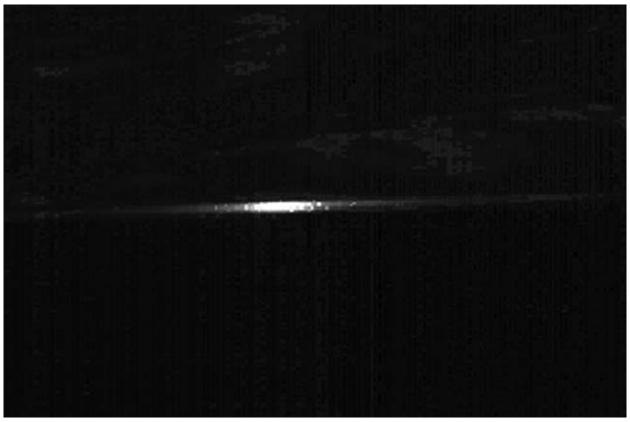

Figure 11 First evidence of the near field of guided modes at 1550 nm for an inverted rib waveguide with a 50-μm width.

iv. To evaluate the linear losses due to substrate leaky modes, these losses are calculated using transfer matrix formalism[11,12] by considering a planar waveguide of homogeneous permittivity $\varepsilon_g = n^2_{P3OT}$, of thickness $t = 2.2$ μm, between the air ($\varepsilon_A = 1$), and a homogeneous cladding layer of permittivity $\varepsilon_c = n^2_{PMMA}$ of thickness $t = 5$ μm deposited on silica film. As a result, the radiative losses are very low, inferior to 10^{-11} dB/cm for the different modes. The values are in the same order of magnitude at 1330 nm. So in our study, the losses due to substrate leaky mode are considered to be negligible.

By comparing the measured loss values and the theoretical loss contributions, the losses would be principally due to the contribution of surface and volume scatterings. In fact, the absorption coefficient induces low losses and does not explain the evolution of the optical losses as a function of the wavelength. Moreover, the radiative losses are negligible and the measured roughness on similar polymers[13] is very low, of a few nm. Therefore, the surface losses could not be the major source of losses. Moreover, the surface scattering losses become important when the interface roughness increases. However, these losses increase slightly with the wavelength. So, even if these surface losses exist, but they do not explain by themselves the decrease in losses with wavelength. We could think that the other cause of losses is volume scattering due to the insoluble particles which occur when the polymer is synthesized. These volume scattering losses would explain why losses vary as a function of the wavelength. In fact, since polymer single fibers were synthesized by purification in the vapor phase, the loss values were lower and were equal to about 0.2 dB/cm at 1550 nm.[14] Moreover, the optical losses were also measured on the "bulk" polymer purified by a vapor phase: scattering losses were inferior to 0.12×10^{-2} dB/cm.[15,16] So the purification step is essential to obtain polymers with good optical properties.

In the case of P3OT, our synthesis requires a large quantity of insoluble $FeCl_4$ catalyst which is not the case for PMMA polymerization. The Fe ratio has been measured in our polymer at around 110 ppm (that means 110 μg/g). In the most unfavourable case, all the Fe content would form spherical particles of 100-nm diameter. We have calculated that the number of particles obtained would be around 1000 particles for a 1-cm waveguide length (and with a section area of 30 μm^2). This corresponds to a particle density inferior to 10^{16} m^{-3}. Considering the index contrast, the size and the density of particles in Figure 9, we consider that scattering losses of the Fe residue provoke excessive losses around 2 dB/cm at 1330 nm and around 1 dB/cm at 1550 nm. The existence of these particles could be the principal origin of the optical losses and explain the optical loss variation as a function the wavelength.

So, by reducing the quantity of insoluble particles and having a better control of the interface roughness, the P3OT film with its specific nonlinear properties could have an excellent potential to make optical waveguides for application in different fields such as optical communication.

Inverted rib waveguides

Moreover, for optic integrated devices, some inverted rib structures were formed based on P3OT and were characterized by measuring optical transmission. Figure 11 represents the near field of guided modes. For the widths of 50–300 μm, the loss values were nearly constant and were around 3.2 and 2.3 dB/cm at 1330 and 1550 nm, respectively, (Table III). The optical loss values are around to those measured on planar waveguides because of the important width of these inverted rib waveguides which are similar to planar waveguides. These results permit the experimental and theoretical optical losses obtained on planar waveguides to be confirmed. In fact, the radiative and scattering losses were calculated for planar waveguides to obtain the principal origins of optical losses.

Unfortunately, the measurement of losses could not be performed on the lower widths (10, 8, 6, and 4 μm) because the cleavage of input faces was not of sufficiently high quality and also because the surface scattering losses could increase drastically in the case of single-mode waveguides (with the lowest widths). Indeed, the polymer film was very easily damaged and had a tendency to lift off. Moreover, these loss values were slightly superior to those obtained on slab waveguides. In the case of strip waveguides, we should take into consideration the loss origins obtained using planar waveguides and the few defects due to photolithography process. In fact, as the overlap between guided modes and interface increases, the participation of surface scattering becomes more important. This could explain the difference in losses between planar and strip waveguides. These optical losses could strongly increase with the reduction in waveguide width that is why the light propagation was not observed for the lower widths.

CONCLUSION

Since, in previous works, we did not observed any propagation in ridge and strip loaded single-mode waveguides based on poly(3-alkylthiophene), we have investigated the different causes of optical losses. This article has presented the analysis of the different loss factors that can be involved in light attenuation with this material. We have measured and studied optical losses of planar waveguides based on P3OT film at different wavelengths using two different methods. Optical losses as low as 1.8 dB/cm were measured at 1550 nm in planar and multimode inverted rib waveguides. These losses in the multimode guides are principally due to surface and volume scattering losses, due to roughness, and notably the presence of insoluble particles which occur during polymer synthesis, respectively.

Moreover, we have demonstrated the feasibility of manufacturing polymer inverted rib waveguides. The optical losses have been measured for multimode waveguides with large widths but the light propagation is not observed for single-mode waveguide (with small widths). The results suggest that, in the case of single-mode waveguides, the high optical losses could be due to the poor quality of the interface between the P3OT and the cladding material.

As the intrinsic absorption and the quality of films are not involved in optical losses, we can think the P3OT is a good candidate to make highly nonlinear waveguides. To manufacture single-mode waveguides with P3OT as core, further works will concern the improvement of the adherence properties between polymers of cladding and core.

Authors acknowledge support from Région Bretagne and the Regional project, PONANT including FEDER funds.

References

1. Schrof, W.; Andreaus, R.; Mohwald, H.; Rouzouvan, S.; Van Keuren, E.; Wakebe, T. Nonlinear Opt 1999, 22, 295.
2. Ihlein, G.; Menges, B.; Mittler-Nher S.; Osaheni J.A.; Jenekhe S.A. Opt Mater 1995, 4, 685.
3. Schrof, W.; Andreaus, R.; Mohwald, H.; Rouzouvan, S.; Van Keuren, E.; Wakebe T. Nonlinear Opt 1999, 22, 295.
4. Messaad, K.; Bosc, D.; Thual, M.; Henrio, F.; Haesaert, S. Open Materials Science J 2008, 2, 47.
5. Okawa, H.; Hattori, T.; Yanase, A.; Kobayashi, Y.; Carter, A.; Sekiya, M.; Kaneko, A.; Wada, T., Yamada, A., Sasabe, H. Nonlinear Opt 1992, 3, 169.
6. Okamura, Y.; Sato, S.; Yamamoto, S. Appl Opt 1985, 24, 7.
7. Charrier, J.; Anne, M.L.; Lhermite, H.; Nazabal, V.; Guin, J.P.; Jouan, T.; Henrio, F.; Bosc, D.; Adam, J.L. J Appl Phys 2008, 104, 073110.
8. Pirasteh, P.; Charrier, J.; Dumeige, Y.; Haesaert, S.; Joubert, P. J Appl Phys 2007, 101, 083110.
9. Cox, A.J.; De Weerd, A.J.; Linden, J. Am J Phys 2002, 70, 620.
10. Tien, P.K. Appl Opt 1971, 10, 2395.
11. Tamir, T. Guided-Wave Optoelectronics, Springer Series in electronics and Photonics, 1990, p 26.
12. Yariv, A.; Yeh, P. Optical Waves in Crystals, Wiley: New York, 1984.
13. Bosc, D.; Maalouf, A.; Haesaert, S.; Henrio, F. Appl Surf Sci 2007, 253, 6162.
14. Bosc, D.; Toinen, C. IEEE Photon Technol Lett 1992, 4, 749.
15. Boutevin, B.; Bosc, D.; Rousseau, A. Transparent Polymers for optical applications. In Desk References of Functional Polymers; Arshady, R. Ed.; American Chemical Society publisher, 1997, p 489.
16. Bosc, D.; Guilbert, M.; Toinen, C. Facteurs de pertes extrinsèques de FOP en PMMA; Congrès OPTO 89, Paris, April 1989.