

Advanced analysis of optical loss factors in polymers for integrated optics circuits

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ABSTRACT

In the context of optical transmission in the polymer integrated waveguides, transmission losses are a limiting factor for the development of such a technology. In this paper, we analyze the different features that cause optical losses namely intrinsic absorption of the material and light scattering in the bulk. This analysis of optical transmissions mainly in the telecom C-band (1530–1565 nm) and O-band (1260–1360 nm) is based on measurements in bulk material and solutions. These allow to assess the limiting level of losses induced by the material itself. The results can give the intensity attenuation resulting from defects induced by the waveguide processing.

It results that losses by scattering process can reach 0.1 dB/cm at 1550 nm when samples are filtered at 0.2 μm . It is slightly higher at 1320 nm but probably less than 0.2 dB/cm. Most of the optical losses are then due to the intrinsic absorption and can be around 0.7 dB/cm for PMMA, at 1550 nm. Consequently, in the case of channel singlemode waveguides, the global linear loss is higher at this wavelength, and, the additional losses are brought by imperfections of the channel both in the bulk and on the surface. This article also shows that reducing the level of C–H bonds content of the polymers down to $25 \times 10^{-3} \text{ cm}^{-3}$ the material losses are limiting by scattering and can fall down to around 0.2 dB/cm (at 1550 nm).

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1. Introduction

Some amorphous polymers have been extensively studied in integrated optics for many years. They offer interesting opportunities for their implementation as optical waveguides. For example, their optical properties can be tailored to fit the particular refractive index or to provide non-linear optical effects in order to optimize the optical propagation and perform functions of optical signal processing [1]. Considering the materials, a large variety of polymers has been studied to fabricate integrated optical circuits (IOCs) [2,3].

The most frequently used are poly-methacrylate and polyvinyl materials and several polymers derivatives owing to their good optical properties and their easiness to film forming and to waveguide patterning. Polymers IOC are still widely studied for creating tunable filters or EO modulators for the high bit rate for example [4]. In the latter application, polymers with high optical nonlinearities bring their great potential for signal processing very competitive with inorganic materials. Despite their attractive particular properties, polymer waveguides generally have relatively high optical losses of the order of 1–5 dB/cm [5–9] that impede their development. Their level observed per unit of length in these waveguides is typically in the transmission C-band of telecommunications (1530 nm–1565 nm). Generally very few information is

given concerning the intensity for different sources of loss measured in an IOC. Fiber to waveguide coupling efficiency can be occasionally assessed and therefore the global linear losses are extracted from the total [10]. Nevertheless, the total loss level does not provide any information distinguishing the different causes involved in both material and processing technology.

Based on our studies on polymer IOC, we propose to bring to light some key aspects about the causes of losses in waveguides that are inherent to the material and those extrinsic related to the process. This results analysis in the telecom wavelength bands leads to the limiting level of losses induced by the material. By the way, the results can give the intensity attenuation resulting from defects induced by the waveguide processing. This study brings forward in particular the intrinsic absorption of polymers calculated from comparison of optical attenuation of bulk materials and solutions taking into account the number of C–H bonds in the polymer responsible of the main absorption occurring in the near infrared region (NIR). The experiments result in determining the optical limit attenuation in the transmission C-band. It will be confirmed by modelling the absorption bands in this spectral region as well.

In this paper, firstly we briefly remind the fabrication process of all the samples necessary to the optical measurements and then we present the optical characterizations. In a second section, we present the analysis of results in order to discriminate the optical losses features and give their relative importance. Polymers used in this study are those that have allowed us to make some integrated optics functions. Some of them are also widely used

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by other authors. Thus, considering general parameters, as for example the content of C–H bonds in the polymer, some results can be extended to other kinds of polymer materials.

2. Experimental

2.1. Polymer films, rods fabrications and characterizations

For this study we considered poly-methacrylate materials that we generally use for waveguide fabrication such as PMMA (poly-methyl methacrylate), PMMI (poly-methacrylimide) and PMATRIFE (poly-trifluoroethyl methacrylate). PMMA is a material core waveguide material from Aldrich, with an average molecular weight M_w around 1.2×10^5 Dalton and a mass index polydispersity, IP, of ~ 3 . Its Tg (glass transition temperature) is 105 °C. PMMI is a modified PMMA from Degussa that presents a glass transition temperature, Tg, at 150 °C and a higher index than PMMA. Due to its low refractive index, the cladding material (under and over the core) chosen is the PMATRIFE (Fig. 1).

By means of the m-lines method, we measured the refractive index of these polymers at the wavelength of 1550 nm and at room temperature (20 °C). These indexes are 1.409, 1.481 and 1.522 for PMATRIFE, PMMA and PMMI respectively. The low refractive index of PMATRIFE leads to a high index contrast when the core is PMMA or PMMI that also ensures for example to build relatively waveguide small radius of curvature, between 90 μm (with PMMI as core) and 120 μm (with PMMA as core) with minimized irradiative losses in the curves [11].

In this paper, we refer also to a previously studied polymer, the PMAFP (poly-methacrylate of pentafluorophenyl) because it exhibits a low content of C–H bonds (Fig. 1).

In order to measure spectral attenuation of the rough materials, we carry out the fabrication of little rods (~ 1 cm diameter) with thickness from 3 mm to 16 mm. For that purpose, commercial polymer powders are cast to form a rod under a pressure of about 500 MPa and at different sample temperatures up to 200 °C. We have ensured that no change occurs in the optical transmission spectrum of PMMI and PMMA under different conditions of pressure and temperature used in this process. The facets of the rod are polished until the edge surface is smooth enough to minimize the light scattering (roughness < 10 nm).

For optical measurements of polymers solution and solvents, we prepare a mixture of solvent and polymer by the same way as for waveguide fabrication. Polymers were dissolved in trichloro-1,1,2 ethane (TCE) with concentration ranging from 200 g/l to 300 g/l. The solutions were filtered through a 0.2 μm PTFE (poly-tetrafluoroethylene) membrane filter. For the waveguide fabrication, polymer solutions are spin-coated at 1000–4000 rpm on a silicon wafer (3" diameter) [12].

All spectra measurements in the NIR of rods and solutions are made with a Spectrophotometer $\lambda 900$ from Perkin Elmer. With solution samples in glass cells, optical attenuation is measured on 0.5–15 cm optical path length. The optical attenuation is a logarithmic measure of the beam attenuation defined by $-10 \times \log(I_0/I_L)$,

where I_0 is the initial beam irradiance and I_L the irradiance after passing through a sample of thickness L . The attenuation of polymer solutions are calculated taking into account of optical losses due to light reflection at interfaces air–glass and glass–solution. Measurements are made again three times so that the standard deviation is as small as possible. Thus whatever the sample solution or rod measured with these conditions, we consider that deviation of the linear attenuation is better than 0.01 dB/cm.

3. Background of optical losses in polymers

Waveguide attenuation, measured from the input fiber to the output fiber is due to different phenomena that can be stated as follows:

(a) Coupling losses:

- Reflection losses at the air – waveguide tip of which the minimum value is given by the Fresnel law between the two optical surfaces orthogonal to the beam. They are around 0.2 dB for dioptries air/polymer if its index is 1.50.
- Losses due to mismatches between modes of input fiber and waveguide. These can be calculated knowing the diameter of the respective modes.
- Additional losses at the input due to the imperfections at the dioptrie interfaces. They depend on the edge quality cleave and therefore the mechanical properties of materials involved in waveguide and substrate.

(b) Transmission losses:

- Light scattering losses due to the surface imperfections (roughness) mainly due to the quality of the lateral sides etching of the waveguide channel and the channel surface quality as well.
- Losses due to lacking adhesion between the cladding and the waveguide core or surface irregularities of the channel.
- Light scattering losses in the material due to dusts and insoluble particles.
- Intrinsic light scattering losses due to the degree of order of “amorphous network.” In the 80's and for completely amorphous polymer materials such losses have been confirmed as negligible compared to the intrinsic absorption [13].
- Losses due to intrinsic absorption of the material caused by the vibration of covalent bonds and electronic conjugation in the molecule of polymer.

In summary, the maximum of transmission intensity, through waveguides that can be expected to reach, can be limited by the intrinsic absorption losses. Transmission measurements made through the waveguides give a global value incorporating all these causes. Some of them can be calculated (dioptrie reflection, modes mismatch). For others it is important to discriminate between the different factors of losses in order to work towards losses reducing.

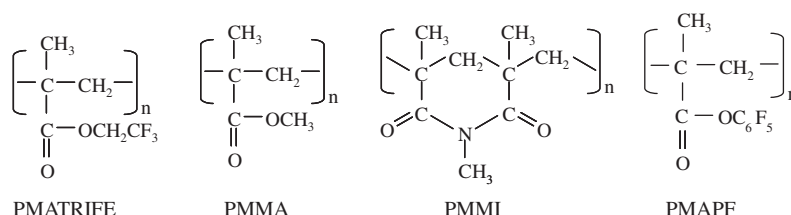


Fig. 1. Chemical structure of polymers used in this study.

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