Polymer Waveguide Technologies for Optical Interconnects

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Abstract: *Basic polymer waveguide technologies actually applied for optical interconnects are reviewed with main emphasis on optical waveguide layers for integration in electrical-optical circuit boards. Main part of the paper is devoted to a technology based on Polydimethylsiloxane (PDMS) as low cost, low loss (0.05dB/cm at 850 nm) and high temperature stable (> 260°C) material system. The optical properties of the implemented materials and realized waveguides are discussed as well as a set up for a first industrial production line of electrical-optical circuit boards.*

1. Introduction

Next-generation internet switches and high-end computers are expected to process aggregate data rates in the order of Tbit/s. In consequence, the interconnections between the processing units will have to handle data rates in the order of 10-40 Gbit/s. It is, however, well known from basic physical laws that electrical interconnections will suffer from high transmission losses and severe signal integrity problems at such data rates [1, 2]. In order to overcome the evident high-speed interconnection bottle-neck, optical interconnects are considered the preferred option. In Gbit/s-rack-to-rack interconnections with link lengths in the order of several meters, the widespread solution is the commercial fiber-ribbon cable in combination with high speed parallel OE-modules. If, however, interconnection lengths come down to the order of 1m, e.g. in backplanes, integrated optical waveguides are considered more economical [3].
The integration of optical waveguides in printed circuit boards as well as in backplanes imposes severe requirements on the materials and processes involved. Some of them are: High transparency of the waveguide materials (< 0,1dB/cm) in the standardized interconnect wavelength window of 850 nm, high temperature stability to overcome standard multilayer printed circuit board lamination process temperatures at 180°C for two hours and especially the soldering process temperatures of 260°C, large area processing capability (> 0,5m x 0,5m), and cost effective mass production.

2. State-of-the-art in polymer multimode waveguide technologies

Among the waveguide technologies studied worldwide for the production of electrical-optical circuit boards, photolithography is the most popular to define the multimode waveguide core structure. Both, direct laser writing and mask exposure techniques are being applied (see Fig. 1)

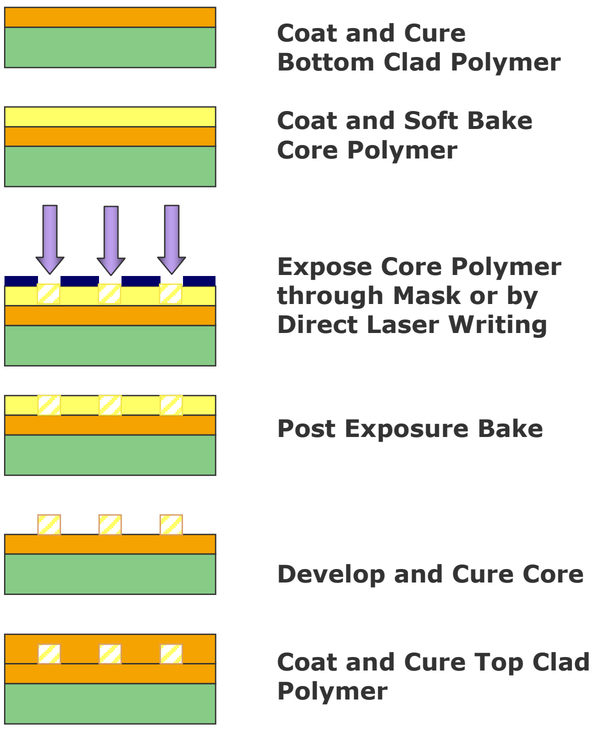

Fig. 1: Polymer waveguide fabrication by photolithography

A considerable variety of temperature stable polymers has been developed for this technology: epoxies [4,5], modified acrylates [6,9], and polysiloxanes [10-13]. Waveguide data obtained with theses techniques and materials are summarized in Table 1.

Material manufacturer	Material	Thermal stability °C	Optical waveguide loss at 850nm dB/cm
Microresist Techn. [4,5]	Epoxy	>200	0,1-0,2
Optical Crosslinks [6,7]	Acrylate	>200	0,08
Exxelis [8,9]	Acrylate	>250	0,04
Dow Corning [10,11]	Siloxane	-	0,04
Rhom & Haas [12,13]	Siloxane	>250	0,03

Table 1: Performance data of reported photopolymer materials and waveguides

Although the photopolymer waveguides reported in Table 1 show excellent performance their industrial implementation in large area boards is critical because of high material costs (>1000 €/l).
Furthermore, hot embossing has been investigated as a suitable technology for multimode polymer waveguide fabrication [14,15]. However, problems may arise from insufficient high temperature stability of optical thermoplastic polymers (for T>200°C) as well as from difficulties with the required high precision at large areas.
In this paper we will focus on a waveguide technology based on casting of thermally curing polysiloxanes which comprises all essential features for a low cost mass production of large area electrical-optical circuit boards.

3. Polysiloxane Waveguide Materials

3.1 Optical loss and thermal stability of bulk PDMS materials

High transparent polysiloxanes are widely used in electronics industries, e.g. to encapsulate LEDs. In addition to the low optical loss, the advantages of polysiloxane for integrated optical waveguide fabrication in printed circuit boards are the high thermal stability, the extreme moulding precision, the large area process ability and especially the low cost (in the order of 50-100€/l). The transmission loss of optical grade polysiloxane bulk samples of different suppliers has been measured to 0.02 – 0.04 dB/cm in the 850 nm wavelength window.

In this paper, two-component room temperature cross linking polysiloxanes of Wacker Chemie GmbH, Burghausen, Germany, have been used. The cladding materials are standard commercial polymers, whereas the core polymer is a special development of Wacker in close cooperation with the University of Dortmund. The transmission spectra of core and cladding materials are almost identical.

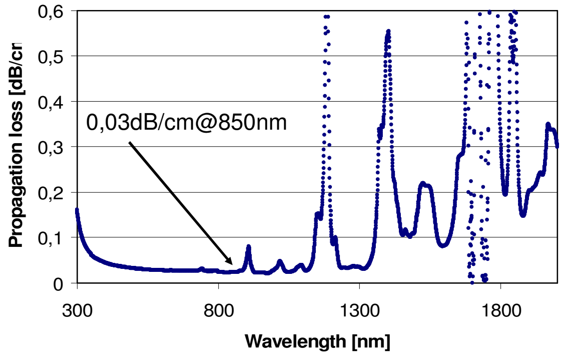

Fig. 1: Spectral transmission of bulk PDMS (Wacker)

The thermal stability of the polysiloxane materials has been studied by comparing the transmission spectra of bulk samples after curing them at room temperature, after a subsequent exposure at 180°C for two hours and after a final exposure at 260°C for five minutes (Fig. 2). This temperature treatment simulates the real process conditions at multilayer board lamination and at reflow soldering. Except in the ultraviolet region (200 nm to 400 nm) there is no significant change in the optical transmission loss. A slight increase in transmission loss is observed only at temperatures above 270°C which makes the material very suitable even for lead free soldering processes.

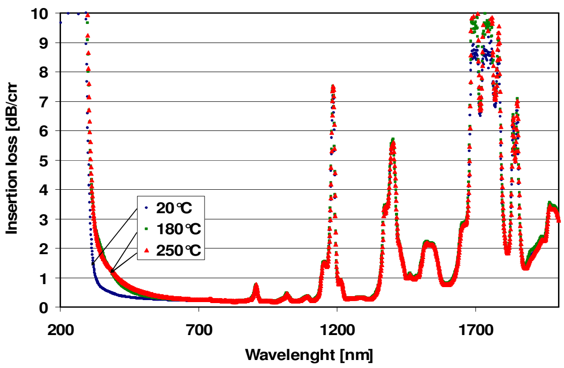

Fig.2: Influence of thermal treatment on transmission loss of bulk PDMS

3.2. Dispersion curves of PDMS bulk materials and their influence on waveguide numerical apertures

The numerical aperture *AN* – resulting from the index difference between core and cladding – is an important parameter in optical waveguides. It defines the optical coupling efficiencies in and out of the waveguides, the bending losses and the transmission bandwidth. To meet an *A*N of about 0,25 by the actual PDMS system, the index of the core material has been tuned to ≈ 1.43 by implementing phenyl groups in the side chain of the PDMS backbone, whereas the cladding material is unmodified PDMS with a refractive index of 1,41. The refractive indices of both components have been measured as a function of wavelength using an "Abbe-Refractometer". In Fig. 3 the dispersion curves of Wacker PDMS cladding and core materials are shown together with Sellmeier fitting curves and respective *A*N values at a temperature of 20 °C. The requirement of an *A*N below 0.26 at 850 nm wavelength results from data transmission rates of 10 Gbit/s over interconnection distances of 1m.

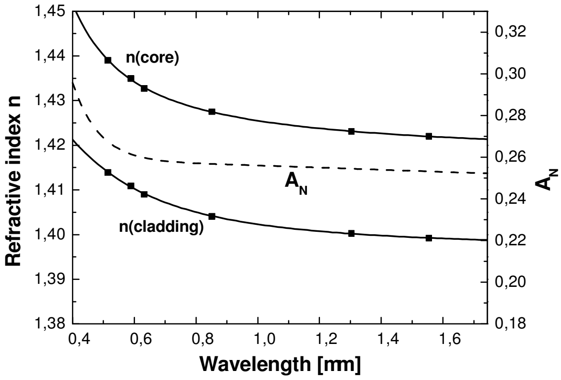

Fig. 3: Dispersion curves of cladding and core material (left axis) and resulting *A*N (right axis) at *T* = 20 °C.

In Fig. 4, the refractive indices at λ = 589 nm are plotted as a function of temperature including the thermo-optic coefficients (TOC) which are in the order of −3.6×10−4 K−1. From Fig. 4 we conclude that *A*N is almost constant in the temperature range between 20 and 55 °C resulting in a nearly athermal waveguide behavior.

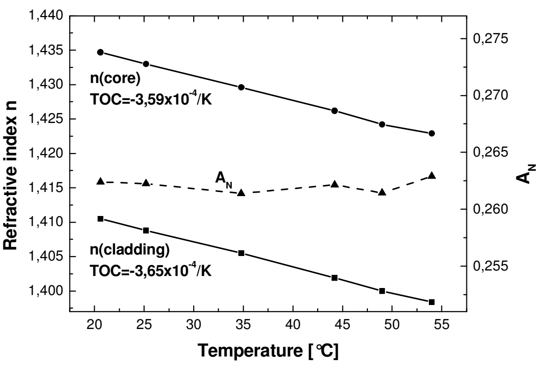

Fig. 4: Refractive indices of cladding and core material at λ = 589 nm as a function of temperature (left axis) and resulting *A*N (right axis).

4 . Fabrication of waveguide layer and board integration

Reactive ion etching and UV-curing have been reported for waveguide fabrication in polysiloxane. We have adopted casting in combination with the doctor blading technique as a new low cost polysiloxane waveguide fabrication method [16,17]. One of the advantages of this technology is that it has the unique feature of simultaneous fabrication of optical waveguides together with integrated micro mirrors for efficient OE-module coupling. Furthermore, casting in combination with the doctor blading technique is well compatible with large area printed circuit board production technologies.

First a casting mould for the waveguide core layer is generated. This is accomplished by SU-8-photolithography and, if required, by subsequent electroplating. In the reported experiments standard 6"-photoresist technology has been applied, but currently extension to larger formats (300mm x 400mm) is under work. In case of large area formats, doctor blading is used instead of spin coating because of the better thickness uniformity of the resist on rectangular substrates. The resist is dried and exposed through a photolithographic mask. After development of the resist the master mould is finished. In order to obtain a mechanical stable mould for mass production an electroplated copy of the resist mould may be realized. The complete production process of the optical layer is shown in Figure 5.

First, the waveguide cores are fabricated by filling the grooves in the mould by the core polymer (n = 1.43). This is accomplished by the doctor blading technique which is easily applicable to large formats. Then the core material is thermally cured.

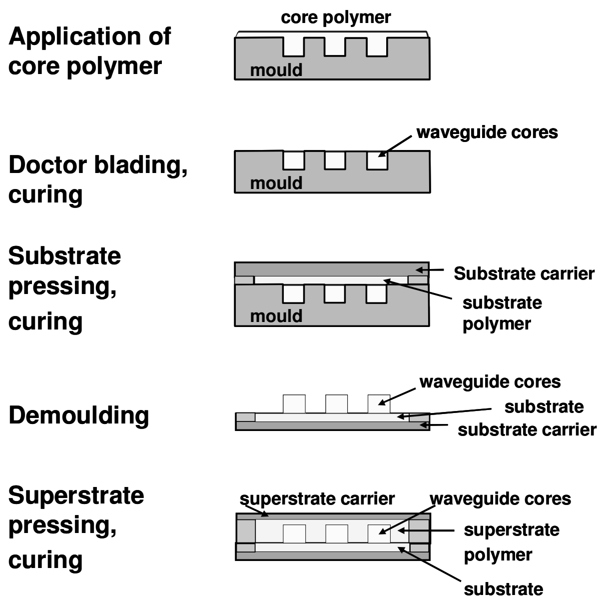

Fig. 5: Scheme of fabrication process of optical waveguide layer embedded between two thin PCB carrier sheets (FR4 or Kapton)

The next step is the preparation of the substrate carrier. One function of this carrier is the mechanical stabilization of the thin optical layer during the subsequent production steps. At the same time, the carrier serves as interface to adjacent PCB layers in case of a multi layer board. It is obvious to use conventional circuit board laminates like FR4 or Kapton. It is advantageous to use copper clad material, since the copper can be structured by standard processes and these structures are well suited to define the thickness of the substrate polymer.
Another function of the copper structures is the prevention of pressure on the waveguide layer during multilayer PCB lamination.
The waveguide substrate layer is fabricated by applying the liquid cladding polymer (n=1.41) to the mould (which still contains the cured cores) and, subsequently, the substrate carrier is pressed against the mould. Now, the copper structures will define exactly the thickness of the waveguide substrate layer. After curing the complete layer comprising cores, substrate layer and carrier is demoulded. Excellent adhesion between the substrate carrier and the PDMS substrate layer could be achieved by using special adhesion promoters.
The production of the superstrate layer is performed by the same technique using identical cladding polymer. Figure 6 shows the cross section of a realized electrical-optical PCB using Kapton ™ (Dupont) substrate carriers. The waveguides have core sizes of 70µm x 70µm and a numerical aperture of 0.26.

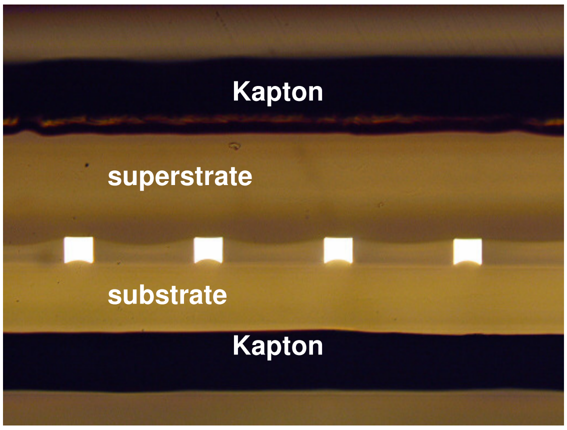

Fig. 6 Cross section of PDMS optical waveguide layer embedded between Kapton™ laminates

4. Optical transmission loss and thermal stability

The waveguide loss has been measured by exciting the waveguides using a 50µm-GI-fibre and collecting the transmitted light by a 200µm-SI-fibre. Typical waveguide loss figures at 850 nm are 0.05 dB/cm measured by the cut back method. The thermal stability has been tested at the PCB-lamination temperature of 180°C for 2 hours followed by an exposure at 220°C and 260°C for 5 minutes to simulate reflow soldering conditions (see Fig. 7)

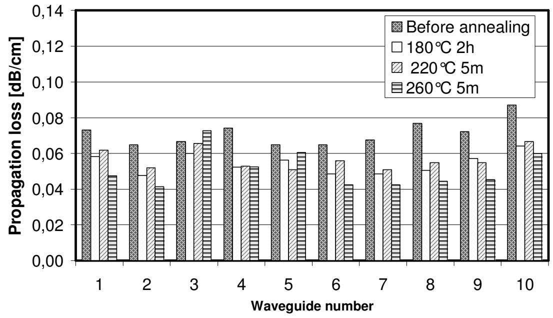

Fig. 7: Thermal behavior of the transmission loss of PDMS waveguide layer

5. Production technology

The described fabrication process developed in laboratory scale at the University of Dortmund now is transferred to an industrial production line (format 460 × 305mm2) within the framework of the BMBF-founded research project "ProSPeoS" [18]. In Fig. 8 a schematic configuration of the basic elements of the production line is shown. In a first attempt the line is conceived in a way that the samples pass through several times according to the sequence of the production steps. A mobile stacker is placed in front and at the end of the line for easy sample handling and transportation. The samples (14 samples at once) are stored in the stacker after one production cycle and inserted at the beginning again. The production unit consists of three main elements: A spray coater, a blading unit and a curing oven. In between there is space for manual operations like sample handling and retooling works.
The first unit is a spray coater (Systronic/ Mühlbauer) where the moulds are coated with PDMS and adhesion promoter, respectively. The automated blading unit is specially developed by ASEM GmbH, Dresden, in close cooperation with the University of Dortmund. Here the core material is applied by a peristaltic delivery, followed by blading and carrier lamination. In the curing oven the polymers are cross linked. Alternatively to inline curing the whole stacker could be placed into a fan oven. For producing the complete optical layer four cycles through the basic line of Fig. 8 are necessary. In order to be processable by the shown processing techniques the basic PDMS materials had to be modified. To enable spray coating, the cladding material was blended by silicone oil to lower the viscosity to values < 1000mPa s. By spray coating PDMS layer thicknesses between 20 and 200µm could be achieved. To extend the pot life of the

processable PDMS materials from a few hours to some days inhibitors have been used. A critical point in using PDMS materials in EOCBs is the realization of a mechanically stable interface between the optical PDMS layer and the adjacent PCB materials like FR4 or Kapton. Substantial work has been invested in the development of suitable surface treatments of the carriers and high-efficient adhesion promoters

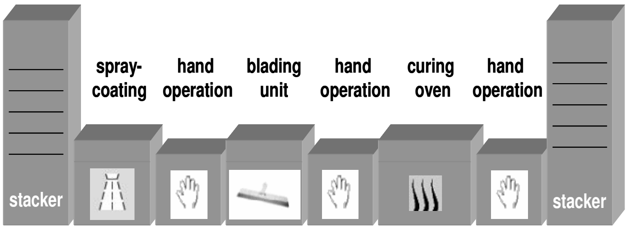

Fig. 8: ProSPeoS production line for optical waveguide layers

6. Conclusion

For polymer waveguide fabrication intended for optical interconnects at $\lambda = 850$nm, a variety of high performance polymer material systems are commercially available: epoxies, acrylates, and siloxanes showing low optical loss figures (<0,1 dB/cm) and good thermal stability (> 200°C). Furthemore, it has been demonstrated, that the developed PDMS waveguide technology is compatible with industrial printed circuit board production technology and is based on low cost polymers.The produced waveguide layers exhibit low optical loss (< 0.05 dB/cm) and high-temperature stability (> 260 ◦C).

Acknowledgements

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