Electrical-Optical Circuit Board Using Polysiloxane Optical Waveguide Layer

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Abstract

This paper reports on a new technology for the realization of an optical waveguide layer in electrical-optical circuit boards. The technology is based on casting of transparent polysiloxanes as low cost, low loss (0,05 dB/cm at 850 nm) and high temperature stable (> 250°C) material system. The waveguide layer fabrication will be discussed as well as the preparation of suitable casting moulds. Further issues are the material and waveguide properties of optical polysiloxanes, the coupling to OE-modules, and the lamination of optical layers into printed circuit boards.

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/. 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 fibre-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 /2/.

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 (< 0,1 dB/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 230°C, large area processing capability (> 0,5m x 0,5m), and cost effective mass production.

Among the waveguide technologies studied worldwide for the production of electrical-optical PCBs, photolithography is the most popular to define the multimode waveguide core structure. Both, direct laser writing /3/ and mask exposure techniques /4/ are being applied. A considerable variety of temperature stable polymers have been developed for this technology: modified acrylates /4,5/, polysiloxanes /6,7,8/, and epoxies /9,10,11/.

Waveguide data obtained with theses techniques and materials are summarized in Table I.

<table>
<thead>
<tr>
<th>Company</th>
<th>Material</th>
<th>Thermal stability °C</th>
<th>Optical loss at 850nm dB/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luvantix /9/</td>
<td>Epoxy</td>
<td>&gt;250</td>
<td>0,04</td>
</tr>
<tr>
<td>KIST /10/</td>
<td>Epoxy</td>
<td>220</td>
<td>0,36</td>
</tr>
<tr>
<td>NTT /11/</td>
<td>Epoxy</td>
<td>&gt;200</td>
<td>0,1</td>
</tr>
<tr>
<td>Zen Photonics /5/</td>
<td>Acrylate</td>
<td>&gt;250</td>
<td>0,05</td>
</tr>
<tr>
<td>IBM /4/</td>
<td>Acrylate</td>
<td>&gt;250</td>
<td>0,04</td>
</tr>
<tr>
<td>Daimler Chrysler /3/</td>
<td>Unknown</td>
<td>&gt;250</td>
<td>0,04</td>
</tr>
<tr>
<td>RPO /6/</td>
<td>Siloxane</td>
<td>&gt;250</td>
<td>0,1</td>
</tr>
<tr>
<td>Dow Corning /7/</td>
<td>Siloxane</td>
<td>&gt;200</td>
<td>0,06</td>
</tr>
<tr>
<td>Shipley /8/</td>
<td>Siloxane</td>
<td>&gt;250</td>
<td>&lt;0,1</td>
</tr>
</tbody>
</table>

Table I: Performance data of multimode waveguides fabricated by photolithographic methods

Although the photopolymer waveguides reported in Table I show excellent performance their implementation in large area boards is critical because of the high material costs.

Furthermore, hot embossing has been investigated as a suitable technology for multimode polymer waveguide fabrication /12,13/. 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 present a new 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.

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.
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.

**Fig. 1: High replication precision in PDMS: Moulded Y-splitter**

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. 2)

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 230°C for five minutes (Fig. 3). 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.

**Fabrication of waveguide layer and board integration**

Reactive ion etching and UV-curing have been reported for waveguide fabrication in polysiloxane /14,15/. We have adopted casting in combination with the doctor blade technique as a new low cost polysiloxane waveguide fabrication method. 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 blade 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 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 (Fig. 4).

In order to obtain a mechanical stable mould for mass production an electroplated copy of the resist mould is realized.

**Fig. 2: Spectral transmission of bulk PDMS (Wacker)**

**Fig. 3: Thermal stability of PDMS**

**Fig. 4: SU-8 master form with straight waveguides**
The complete production process of the optical layer is shown in Fig. 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.

The next step is the preparation of the substrate carrier. One function of this carrier is the mechanical stabilisation 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 from 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 (n = 1.41) and a superstrate carrier with copper structures to define the thickness of the superstrate layer.

Fig. 6 shows the cross section of a realized electrical-optical PCB using FR4 substrate carriers. The waveguides have core sizes of 70µm x 70µm and a numerical aperture of 0.26.

An alternative carrier material in particular with regard to flexible board applications or very high temperature stability is the polyimide film Kapton® (Dupont). In Fig. 7 the cross section of such a laminate with Kapton® is shown.
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.(see Fig. 8) The thermal stability has been tested against the PCB-lamination temperature at 180°C for 2 hours followed by an exposure at 230°C for 5 minutes to simulate reflow soldering conditions. Fig. 8 shows the results of these thermal stability tests.

![Fig. 8: Thermal stability of PDMS waveguide layer](image)

If embedded between two Kapton carriers the optical waveguide could be annealed up to 260°C without observable increase of the optical loss. There is even a tendency of improvement of the optical transmission after the exposure to higher temperatures.

![Fig. 10: SEM-photo of milled micro mirrors](image)

Coupling to OE-modules

Besides the integration of an optical waveguide layer in a PCB, the optical coupling in and out of the board is of crucial importance for the success of the concept of optical interconnections in PCBs. In this paper a micro mirror technology is proposed /16/ which is well compatible to the described replication process. The basic idea is to realize the mirror structures already at the masterform level and apply the waveguide layer fabrication as outlined.

![Fig. 11: Waveguides with integrated micromirrors and MT–pins for passive OE-module coupling](image)
High speed data transmission

In order to test the high-speed transmission capability of the fabricated boards, a 850nm emitting VCSEL and a pin-photodiode have been butt-coupled to the waveguide layer of a 12 cm long multi layer board at the University of Ulm (Department of Prof. Ebeling) (see Fig. 12). Digital data at a rate of 10 Gbit/s have been transmitted with bit error rates less than 10^{-12} (Fig. 13). The transmission speed was limited by the photodiode /17/.

Conclusion

Polysiloxane waveguide technology has been demonstrated to have low optical transmission loss (0.05 dB/cm at 850 nm), high thermal stability (> 250°C) and large area process ability using casting and doctor blade techniques. Being highly compatible with printed circuit board technologies the casting of polysiloxane fulfils all requirements for a successful development of large size electrical optical circuit board production.

Acknowledgement

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