Multimode Waveguides of Photodefinable Epoxy for Optical Backplane Applications

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We developed photodefined, multimode-fiber compatible waveguides based on epoxies. These waveguides will be embedded in backplane PCB's for optical interconnect applications using 850 nm VCSELs as light sources. Apart from very low loss, the material selection took into account, PCB compatibility and low yellowing due to high temperature processing (for PCB lamination and soldering). The waveguides showed losses < 0.06 dB/cm at 832 nm and 633 nm. Their loss increase after aging (1 hr at 185 °C) was limited to 0.04 dB/cm at 850 nm. Waveguides realized on FR-4 (epoxy-fiberglass) PCB material are demonstrated.

Introduction

The continuous increase of the microprocessor clockrate (expected clockfrequency ~10^{10} Hz in 2011), in addition to the continuous increase of data rates in optical transmission systems, has created a bottleneck in high- end systems like servers, and telecom switches, at the interconnect between cards over their PCB (Printed Circuit Board) backplane. In those systems, aggregate data rates of multiple Tbps have to be transported via the backplanes over a typical distance of about 0.5 m. and with such bandwidth-distance products, the electrical data transmission through a copper line is touching its fundamental limit around 20 Gbps. Optical transmission via waveguides offers the potential of a much larger capacity. Therefore, there is worldwide an intense research activity ongoing to realize Optical Backplanes. These are backplanes with an embedded multimode polymeric optical waveguide layer, equipped with in- and output couplers, fabricated with PCB compatible, low-cost fabrication techniques [1,2].

In [3] we reported on a photodefinable epoxy formulation with attractive properties for Optical Backplane applications. However, a drawback of this material is its increase of attenuation at 850 nm from 0.1 dB/cm to 0.4 dB/cm due to yellowing after the high temperature processing step (1 hr, 180 °C) which is applied in PCB lamination process. The high content of the aromatic diglycidyl ether of bisphenol-A (DGEBA) prepolymer in the formulation can largely be held responsible for that. Therefore, we have replaced most of the aromatic epoxy by (saturated) cycloaliphatic epoxies which are known to yield less yellowing after aging. This paper shows the superior properties of the new formulation.

Cycloaliphatic epoxy formulation

An important requirement is the solid nature of the epoxy material for the waveguide core. This prevents the latent image of photoacid catalyst that is formed in the epoxy matrix after masked uv- exposure to fade by diffusion. Moreover, a solid core material layer is required for contact masking.

A cycloaliphatic epoxy prepolymer (code name CHEP) was identified as a suitable material. It features, apart from a low epoxy equivalent weight, a high glass transition temperature of about 200 °C (cured polymer) and a low content of ionic impurities.

A drawback of (cyclo) aliphatic epoxies is their relatively low refractive index (n~1.5), compared to aromatic (e.g. DGEBA) epoxies (n~1.6). This makes it difficult to find cladding materials, which should have indices 0.013 lower than the core material in order to make waveguide channels having a numerical aperture (NA) that is compatible with multimode fibers (50 µm core, NA= 0.2).

Therefore CHEP for the core material was blended with DGEBA to raise its index. To reduce the sensitivity for cracking as a result of the high glass transition temperature, a polyol was added to the formulation. This additive is known to improve the polymer flexibility. In addition, it enhances the cure rate. We applied a high-purity triol. Other additives are an anti-oxidant, an adhesion promoter and a flow and leveling additive. Fig. 1 shows the refractive index at 830 nm of the CHEP-DGEBA-triol film waveguides as a function of DGEBA content as measured with a prism coupler (Metricon).

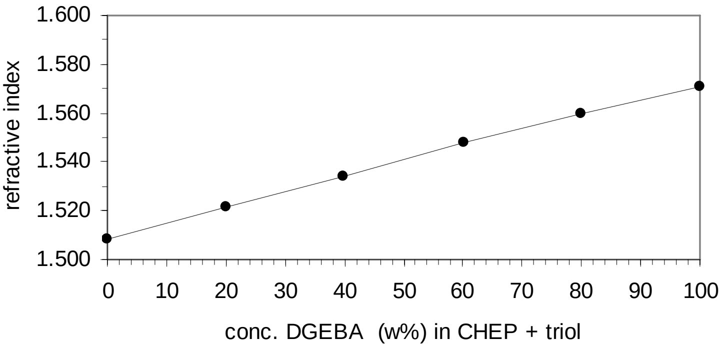
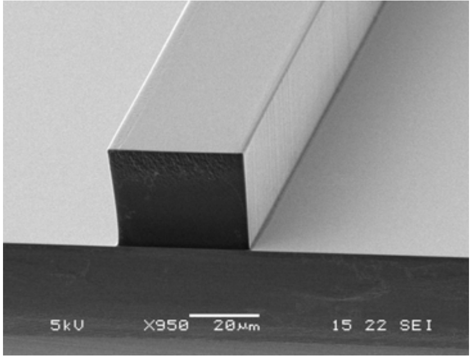


Fig. 1. Refractive index @ 850 nm of CHEP film waveguides as a function of DGEBA content.

From fig. 1, it can be seen that at about 20% DGEBA concentration the required refractive index contrast of 0.013, with undoped CHEP as cladding, can be obtained.

Fig. 2a is a SEM picture of photodefined waveguide core showing very smooth sidewalls and a rectangular cross-section. Fig. 2b shows a microscope picture of waveguides (~40 µm thick and wide) embedded in an undoped CHEP cladding as deposited onto a FR-4 PCB substrate. Excellent planarization can be observed.



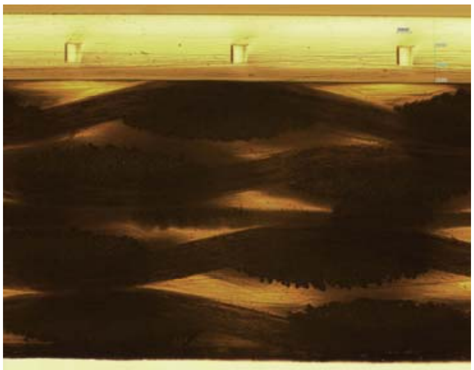


Fig. 2a. SEM picture of a CHEP-DGEBA-triol core. Fig. 2b. Microscope picture of embedded waveguides deposited onto a FR-4 PCB substrate; the fiberglass yarn is clearly visible.

Apart from cracks, the polyol also reduces the UV exposure time. The amount of photoinitiator (triarylsulfonium hexafluorophosphate) could be reduced with 50% while keeping the exposure time in the mask aligner (Karl Süss MA55) the same. This will be beneficial for the reduction of yellowing by photoinitiator residues after high temperature processing.

To allow for accurate loss measurements of CHEP-based waveguides, a very long (103.6 cm) coiled up waveguide, combined with a short (7.2 cm) reference waveguide was made on a 4'Pyrex wafer. The long waveguide is a Fermat spiral as shown in fig. 3a. The radius of the two inner loops is 15 mm.

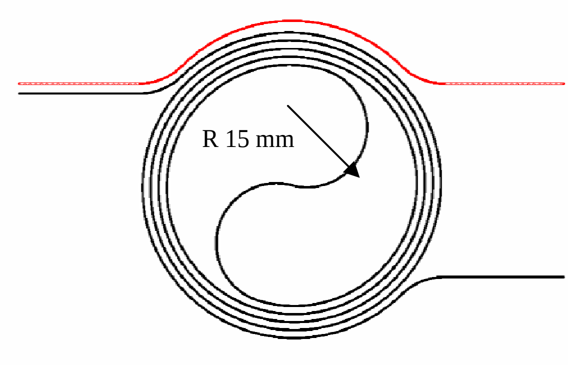


Fig. 3a. Fermat spiral and reference waveguide.

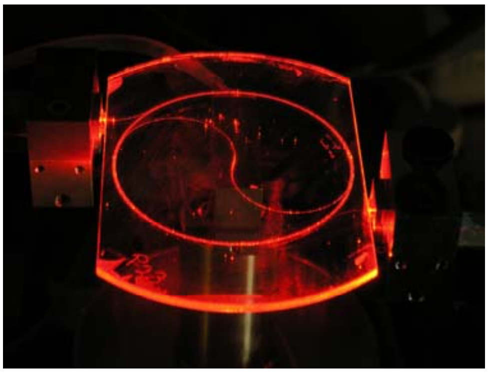


Fig. 3b. Stray light at 633 nm from the spiral.

A relatively high contrast waveguide, with an index difference of 0.03 (NA=0.3) has to be made for this structure in order to keep bend losses in the inner loops to negligible values. To that end, we combined the 20% DGEBA doped CHEP core with a CHEP cladding doped with a low refractive index, difunctional epoxy siloxane. The core was spincoated and photodefined directly onto the Pyrex wafer, and the photocurable cladding was used to adhere a cover Pyrex wafer onto this to protect the waveguide and to allow for dicing of endfaces. Fig. 3b shows the stray light at 633 nm emitted by the waveguide as recorded by a digital camera. The propagation loss at 633 nm was derived from the variation of the intensity in the individual channels as a function of the propagation distance as taken from a small section of a zoomed-in picture (fig. 4a). This is plotted in fig. 4b and yields a propagation loss of 0.04 dB/cm.

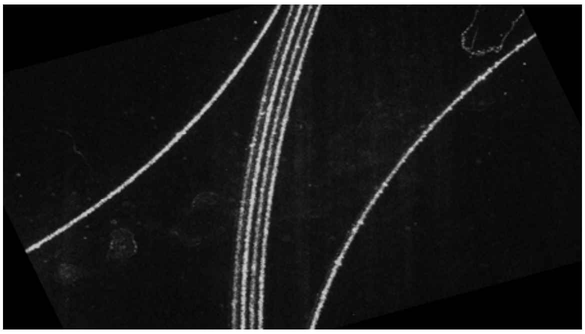


Fig. 4a: Stray light (@633 nm).
Note the alternation in back and forth running channels.

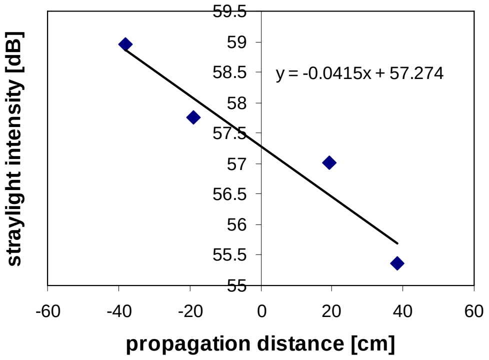


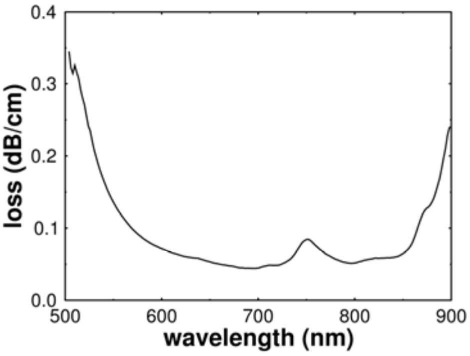
Fig. 4b: Stray light intensity vs. path length.
The zero reference is placed in the centre.

In addition, propagation loss measurements were performed at laser wavelengths of 633 nm and 832 nm using butt-coupled multimode input/output fibers. The propagation loss was derived from the differences in insertion loss (IL) and path length between the spiral and the reference channel. The loss at 633 nm show good correspondence with the stray light measurement result. These results are listed in table 1.

Table 1. Measured propagation losses

Wavelength [nm]	From IL [dB/cm]	Stray light [dB/cm]
633	0.05	0.04
832	0.06	

The spectral dependence of the propagation loss was as measured by injecting white light in the waveguides and analyzing the output using an optical spectrum analyzer (Spectro 320, Instrument Systems). The spectrum have been calibrated on measurement at 633 nm as given in Table 1. The measurement has been repeated after thermal aging of the sample for 1 hour at 185 °C. The results as presented in fig. 4a and 4b show losses around 0.05 dB/cm between 600 and 700 nm and between 800 and 850 nm, while the loss increase after thermal aging is limited to 0.04 dB/cm at wavelengths >700 nm.



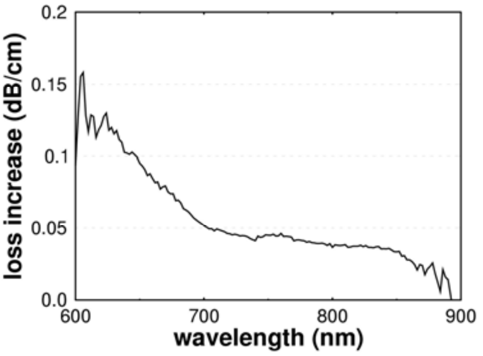


Fig. 4a. Spectral dependence of the prop. loss. Fig. 4b. Loss increase after thermal aging (1hr at 185 °C).

Conclusion

We have presented attractive multimode photodefinable epoxy waveguides for Optical Backplane applications. Multimode-fiber compatible waveguides on FR-4 PCB substrate material have been demonstrated. A propagation loss of <0.06 dB/cm at 850 and 633 nm has been measured. Thermal aging at 185 °C for 1 hour yields a loss increase of < 0.04 dB/cm at wavelengths >700 nm.

Acknowledgement

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