Optical waveguides embedded in PCBs – a real world application of 3D structures written by TPA

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Abstract

The integration of optical interconnects in printed circuit boards (PCB) is a rapidly growing field worldwide due to a continuously increasing need for high-speed data transfer. There are many concepts discussed, among which are the integration of optical fibers or the generation of waveguides by UV lithography, embossing, or direct laser writing. The devices presented so far require many different materials and process steps, but particularly also highly-sophisticated assembly steps in order to couple the optoelectronic elements to the generated waveguides. In order to overcome these restrictions, an innovative approach is presented which allows the embedding of optoelectronic components and the generation of optical waveguides in only one optical material. This material is an inorganic-organic hybrid polymer, in which the waveguides are processed by two-photon absorption (TPA) processes, initiated by ultra-short laser pulses. In particular, due to this integration and the possibility of *in situ* positioning the optical waveguides with respect to the optoelectronic components by the TPA process, no complex packaging or assembly is necessary. Thus, the number of necessary processing steps is significantly reduced, which also contributes to the saving of resources such as energy or solvents. The material properties and the underlying processes will be discussed with respect to optical data transfer in PCBs.

I. INTRODUCTION

The tremendous increase in performance of microelectronic devices is also associated with optical data transfer at increasingly lower distance. The trend to miniaturized devices cannot be prevented anymore while, simultaneously, their complexity and functionality is continuously increasing. The high demand of bandwidth will push optical data connections further forward, where data transfer also will be included into printed circuit board (PCB) technology. Conventional copper technology faces some limitations, for example related to frequency-dependent signal propagation delay and increasing cross-talk upon further reducing the packaging density of electrical connections. However, these limitations in electrical circuitry can be overcome by complex and costly shielding procedures.

In the past years, optical data transfer has revolutionized information and communication technologies. Integrated optical devices are the key components in current and future data transfer technologies, since they enable the substitution of many copper lines without any shielding designs. Optical data transfer is highly superior to electrical data transfer with respect to data rate, operating distance, and electromagnetic compatibility, respectively. Therefore, optical packaging technologies also enable very high integration and allow further miniaturization of devices. Particularly, they are very attractive for mobile applications. The development of optical data lines will tremendously increase the functionality of a PCB, and they will be employed in applications which require highest data rates between devices or modules such as backplanes, or where space-saving designs are needed (e.g., in mobile applications).

The realization of optical data transfer systems integrated in electrical PCBs – so-called optoelectronic PCBs, is discussed for a long time. This realization requires, for example materials which enable the fabrication of optical waveguides with low absorption losses at the signal transmission wavelength in the PCB. In addition to these requirements, the materials need to be completely compatible to the harsh standard PCB production requirements. This means that they need to be combined with standard materials and processes for optoelectronic PCBs, in addition to enable a low-cost production. Up to now, no satisfying material solutions were proposed with respect to performance, simple fabrication of devices in PCB, and a simple assembly, respectively. The performance of optical materials on PCB is often poor, and the fabrication of optical structures such as waveguides in PCB is restricted to a few materials. In addition, the assembly of electro-optical components such as laser and photo diodes to the waveguide is very complex, thus resulting in high costs.

Typically, for the fabrication of waveguides, two materials with different refractive indices are used, where the waveguide's core has a higher refractive index than the waveguide's cladding, accounting for a high enough refractive index difference Δn (n_{core}-n_{clad}). The integration of optical waveguides on board level can be achieved either by employing hybrid approaches using glass or polymer fibers [1], or by polymer waveguides [2] which are fabricated and integrated on or in PCBs by complex procedures. Optical backplanes based on integrated glass or polymer fibers are already commercially available, but they are very expensive. Polymer waveguides enabling low-cost fabrication can be generated by various technologies, among which are photolithography [3], laser ablation [4], embossing [5], or laser-direct writing [6]. However, these technologies typically require many different, sometimes even cost-intensive process steps. Additionally, the integration of the waveguides on board level including in- and out-coupling from and into the waveguides still is a matter of intensive investigations. As materials, often organic polymers are used [7]. As optoelectronic devices emitters such as, for example vertical cavity surface emitting lasers (VCSEL) often working at a wavelength of 850 nm are employed, while photo diodes are used as receivers. Conventionally, in- and out-coupling of the light is often performed via more or less complex integration of mirrors, gratings, prisms or lens systems into the systems (see, e.g., [2,4]).

While the realization of optical waveguides is not a significant challenge anymore, there are two major challenges which are not yet solved satisfactorily: the performance of the optical polymer waveguides, and the optical alignment of the opto-electrical components with active or passive adjustment for the in- and out-coupling of light into and out of the waveguides. Based on this, a direct integration of optical connections into PCBs without the need for complex packaging and complex assembly is anticipated. Thus, a concept is presented which addresses three major aspects for the realization of a direct optical integration into PCBs:

1. The development of a novel concept for the direct assembly of optoelectronic components on the PCB's internal layers,
2. the development of a novel optical inorganic-organic hybrid polymer which is adapted to two-photon absorption (TPA) technology, and which can fulfil the harsh production requirements of the PCB process, and

3. the fabrication of optical waveguides in this hybrid polymer material by TPA without solvent-based processes, i.e. a waveguide fabrication in one and the same material.

In the following sections, the realization of an integrated optical interconnection system in a PCB is described. The results will be discussed with respect to the underlying inorganic-organic hybrid polymer material class and the TPA technology.

II. EXPERIMENTAL

II.1 Inorganic-organic hybrid polymers

II.1.1 General aspects

Inorganic-organic hybrid polymers such as, for example ORMOCER®s [8], are synthesized via catalytically controlled hydrolysis/polycondensation reactions. Using alkoxysilanes, an inorganic-oxidic network is established which is organically modified on a molecular level [9]. Via synthesis conditions such as reaction temperature and time, concentration and kind of the catalyst, nature of the employed solvent as well as amount and kind of the respective alkoxysilanes, storage-stable resins with negative resist behavior can be synthesized, resulting in custom-designed materials. Specially synthesized ORMOCER®s were already developed for microsystem technology in order to be applied in optical interconnects or waveguides [10,11], for microoptics [12,13], in electro/optical applications [14], as dielectric layers [15], and as passivation materials for the encapsulation of microelectronic devices and components [16,17].

The processing of ORMOCER®s typically consists of two steps: (1) The establishment of an organically modified -[Si-O-Si]$_n$- structure, whereas the individual oligomers are in the range of 0.7 to 10 nm, present in a pre-polymer sol. As organic moieties, (oligo-)methacryl or acryl, styryl, or epoxy groups are often used. (2) An organic cross-linking is performed either photochemically and/or thermally.

As already mentioned above, the material properties can be adjusted with respect to the intended application. For example, for near infra-red (NIR) optics Si-OH groups present in the resin or the lacquer can be reduced with silylating agents. With nuclear magnetic resonance (NMR) spectroscopy, it can be shown that di-alkoxysilanes yield chain or ring polymers, while tri-alkoxysilanes can result in three-dimensional networks. By increasing the inorganic content in the hybrid network, the Young’s modulus as well as the mechanical and thermal stability can be increased. This simultaneously leads to a reduction of the coefficient of thermal expansion (CTE) and the optical losses in the NIR regime. The reason for the latter is that the content of SiO_x intrinsically having a low optical loss is increased, while the amount of organic species is diluted within the resin. However, it should be mentioned that the higher the inorganic content, the more brittle the material will be, and the resulting layer thicknesses will also be reduced compared to a more organic material.

The organic polymerizable groups are also chosen with respect to the requirements. For example, for patterning via UV or laser lithography, (oligo-)methacryl or acryl, or styryl moieties are typically chosen. In the case of patterning via screen-printing, epoxy moieties are preferred using thermal cross-linking processes. Non-reactive groups such as, e.g., alkyl or aryl groups which are connected to Si also influence the material properties. An increase of their amount within the hybrid polymer will reduce the degree of polymerization due to sterical reasons, thus resulting in a reduced density within the coated layers. This has direct impact on the optical or dielectric properties such as the refractive index or the permittivity.

Solvents formed upon synthesis are usually removed from the final resin under reduced pressure in order to achieve highest processing flexibility. For thin-film applications, these solvents can be replaced by other solvents being added to adjust the material's viscosity. Most of the ORMOCER® resins have a long storage stability with and without photoinitiators at room temperature which was characterized for selected material systems to be longer than two years.

II.1.2 Characterization of the developed ORMOCER® *material*

For the fabrication of optical waveguides on PCBs by TPA, an acrylic modified material was synthesized. These groups show a higher reactivity in the TPA process if formulated with suitable initiatiors compared to methacryl or styryl groups. The material was used without solvent, and it was modified such that the response to the femotsecond laser pulses is very high in order to account for a high densification of the laser light-exposed areas. In this first approach, 2-benzyl-2-dimethylamino-4'-morpholinobutyrophenone was used as UV initiator, whereas other initiators with higher two-photon absorption cross-section were also employed which will be described elsewhere.

The optical properties of the resulting resin were investigated by UV-VIS spectroscopy, yielding absorption losses of the resin at 850 nm of about 0.02 dB/cm. This is low enough for being applied as waveguide material in PCBs.

The resin's refractive index was determined with an Abbé refractometer at $\lambda = 587$ nm to be around 1.491. Using a prism coupler, the refractive index of UV-cross-linked (I-line) and subsequently thermally cured layers (thickness 9.55 µm ± 0.2 µm) was determined to be $n = 1.523 \pm 0.001$ (at 635 nm). This means that theoretically an index difference Δn of as high as approx. 0.03 could be achieved within one material.

II.2 Two-photon absorption processing

Two-photon absorption (TPA) processing can be applied in order to realize real 3D structures without any complicated processing sequences [18,19]. For the experiments presented in this publication, a pulsed femtosecond laser ($\lambda = 800$ nm, pulse durations between 130 and 150 fs) is focused into the ORMOCER® layer, previously coated onto the PCB substrates. The material has to be highly transparent at the laser wavelength, thus accounting for the possibility of creating structures with high precision deep below the coated layer's surfaces. Within the focal region, the photon density is high enough to initiate an organic cross-linking of the inorganic-organic hybrid polymer, resulting in solidified areas which are surrounded by liquid material. Either solvent-based processes can be employed analogously to conventional UV lithography processing in order to achieve 3D structures [19,20], or the created structures can be further processed by, for example, treating the material thermally (see section III).

Compared to UV or electron-beam lithography, TPA processing allows one to directly create computer-generated 3D structures at very high speed. Due to the very sharp threshold fluence for the TPA process, structure resolutions far beyond the diffraction limit can be realized by choosing a suitable combination of, e.g., the pulse energy and the number of applied pulses [20]. The generation of nm-size structures by TPA can be influenced by the UV initiator and the laser parameters. It could be shown that, beside laser parameters such as power, number of applied pulses, and irradiation time, respectively, the structures are also influenced by the laser wavelength [21]. The latter is directly related to the introduced initiator system in the hybrid polymer material, since the laser intensity is convoluted with the photoinitiator's extinction coefficient. Thus, the absorption cross-section for the two-photon process continuously decreases with increasing laser wavelength or, in other words, the higher the laser wavelength, the less energy is available for the polymerization of the ORMOCER® material. However, for the novel ORMOCER® system, reliable functional waveguide structures can be produced in one material far beyond the initiator's highest cross-section which would be around 660 nm.

Beside the possibility of creating 3D structures in an ORMOCER® material system by TPA, this technology has one major further advantage: waveguides can be fabricated within one and the same material in one step, which significantly reduces production costs and times compared to etching and conventional UV lithography processes. Moreover, this technique allows one to vary the waveguide's shape and size by simply modifying the laser focus (cf., Figure 2).

III. RESULTS AND DISCUSSION

In the following, several aspects of the optical integration concept as well as characterizations will be described and discussed in more detail. Figure 1 shows a principle sketch of the innovative concept of the integration of optical waveguides into the inner layers of printed-circuit boards.

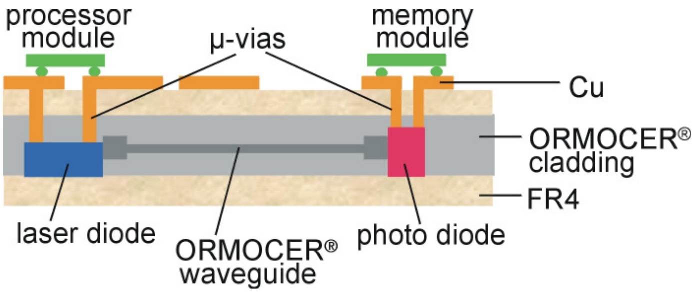

Figure 1 Principle sketch of optoelectronic devices and ORMOCER® waveguide integration into the inner layers of a PCB.

The concept is based on the complete integration of the optoelectronic devices (laser- and photo diode) onto the inner layer of a PCB (cf., Figure 4), followed by their complete embedding by the optical ORMOCER® material. This results in a protection of the mounted optoelectronic components, while simultaneously – due to this integration concept - more space is available on the PCB. Subsequently, the waveguides are fabricated with highest precision by TPA, whereas the waveguides are directly connected to the laser and photo diode, respectively. Simulations concerning the thermal management of the laser diode embedded in the ORMOCER material are discussed elsewhere [22].

Prior to the fabrication of multimode waveguides, the appropriate processing parameters for the laser/ORMOCER® interaction have to be found. For this purpose, screening experiments of, for example, laser power or feed rate of the sample motion are performed. These experiments yield the fabrication window for the material under investigation, i.e. the parameter range for which suitable results can be obtained without damaging the material. For the ORMOCER® waveguides, this means a fairly high index contrast without "burning" the material, while the surrounding non-exposed material forms the cladding layer. Such an induced index contrast by TPA-induced cross-linking is already visible by means of optical microscopy (Figure 2).

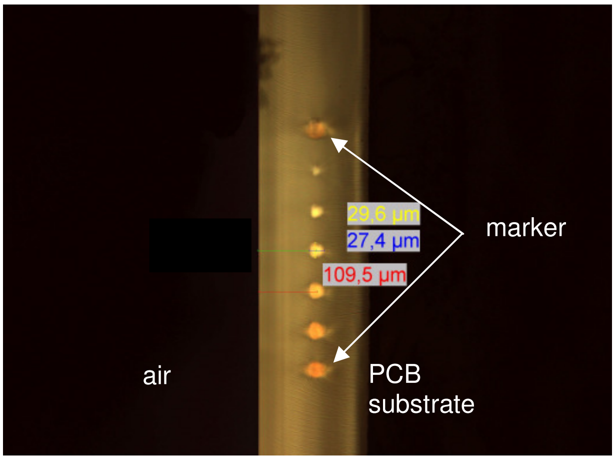

Figure 2 Cross-sectional view of a patterned ORMOCER® layer on a PCB substrate.

The TPA laser is focused into the ORMOCER® layer whose thickness is approximately 190 µm. Upon varying the laser power from 160 to 260 µW (from the top to the bottom) in 20 µW steps, a useful power range for embedded waveguide fabrication can be found. The arrows indicate marker lines written at 260 µW for optical microscopy. The depth of the lines is set to approximately 100 µm beneath the surface of the optical material. The sample is scanned at a speed of 20 mm/min relative to the laser focus. The beam is shaped using an optical setup as described in [23], which results in clearly visible waveguides with a nearly spherical cross-section. The diameter of the waveguides is dependent on the average laser power, and it is typically around 30 µm. Waveguide bundles were written by means of TPA, consisting of 7 individual waveguides with a diameter of approx. 25 µm. The total bundle diameter amounts to approximately 50-75 µm (Figure 3).

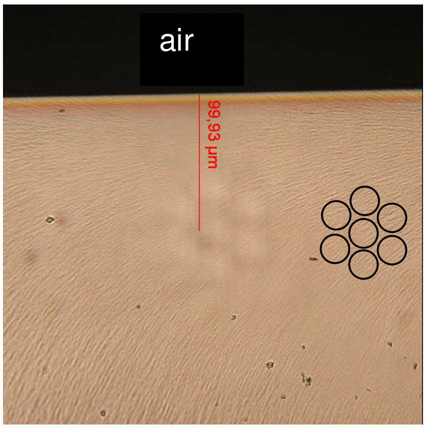

Figure 3 TPA-written waveguide bundle in ORMOCER® (approx. 100µm from ORMOCER® surface) on PCB, consisting of a center waveguide surrounded by six satellite waveguides.

Once the appropriate system parameters for the fabrication of TPA-written multimode ORMOCER® waveguides are defined, the start and end positions of the waveguide have to be determined from the positions of the laser and the photo diode. For this purpose, the diode chips are localized by a machine vision system, which enables the definition of the lateral waveguide end cap positions relative to the diode chip location. The accuracy of this method is approximately 5 µm, and is sufficiently precise for aligning the waveguides with respect to the laser diode (VCSEL) emission point (cf., Figs. 4 and 5).

The 3D capabilities of the TPA-based lithography require also depth information of the sample, because the waveguide is aligned and fabricated in situ as intrinsic part of the writing process. The depth registration of the waveguide's end caps is retrieved from scanning a He-Ne laser vertically through the sample. By means of a confocal optical setup, the intensity of the reflected light is observed and detected as a function of the vertical laser focus position. This allows one to determine the position of the ORMOCER® coating's surface and the top edge position of the laser diode, respectively. The data are then re-calculated, taking into account the ORMOCER®'s refractive index and the laser diode layout in order to precisely determine the depth coordinates of the waveguide positions in front of the laser diode's active emitter area. The same procedure is repeated for the position of the photo diode (cf., Figure 5). The time for the registration of the electro-optical components depends on the quality of the diode chip alignment (e.g., chip tilt), because a bad feedback from the chip edge requires more locations on the chip to be scanned. In comparison to the writing of a several cm long waveguide, this procedure is fast assuming full automization. Up to now, this process step is done manually, and therefore the time consumption of sample gauging is comparable to the duration of the waveguide writing itself.

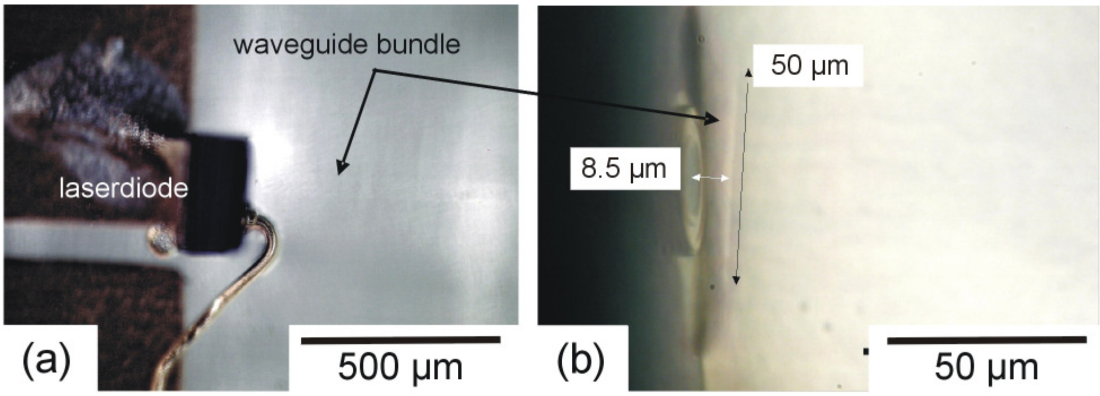

Figure 4 Optical microscopy of the top view of the laser diode chip. (a) Coarse view: VSCEL mounted on a PCB, and ORMOCER® waveguide. (b) Detailed view showing the VCSEL emission area. The bright line at approx. 8.5 µm in front of the VCSEL indicates the waveguide bundle end cap.

After start and end coordinates are defined by the machine vision system, the confocal setup is used for mapping the ORMOCER® coating's surface along the waveguide path. For this purpose, the waveguide is approximated by an interpolating function between start and end positions. The vertices of this function represent the sampling points, where the position of the ORMOCER® surface is determined by vertical scanning of a He-Ne laser. By that, the lateral positions of the waveguides and their depth is controlled over the entire distance between laser and photo diode chip. The principle of referencing the waveguide depths is presented in Figure 5. In Figure 5 (a), a schematic sketch of the laser diode design (front side) is shown. The VCSELs emission point is at a depth Δ_D+A below the ORMOCER®/air interface. By means of a confocal optical setup, the intensity of the reflected light from the ORMOCER®/air interface and from the top edge of the VCSEL chip is recorded as a function of the laser focus' z position (vertical direction in Figure 5 (b)). Each index step at an interface gives a maximum of the reflected light, which can be translated to a depth profile of the sample at the laser diode site. The red line indicates a scan directly over the laser diode, while the black line is measured next to the laser diode chip.

The coupling between the waveguide and the diode chips critically depends on the alignment accuracy of the optoelectronic chips. Slight tilt angles of the diode chips and other mounting imperfections cause a bad feedback signal from the confocal setup, and therefore introduce larger alignment errors of the waveguide. Provided that good feedback signals from the laser and photo diode chips exist, the waveguide can be positioned at an accuracy of a few microns relative to laser and photo diode, respectively. The ORMOCER® film exhibits generally a very smooth surface, which yields a good feedback signal that allows also a positioning of the waveguide relative to the ORMOCER® film surface at micrometer accuracy. This way, the waveguide or waveguide bundle is written at the right position inside the ORMOCER® coating and, in addition, it is already aligned to the optoelectronic components, which are also embedded in the same coating. A very neat feature of this technology is that no cost-intensive alignment and assembly steps have to be performed. The complete optoelectronic PCB is fabricated only with a couple of steps. After fabrication of the optical waveguides by TPA, the next production step is a lamination step at a temperature of 200 °C for 2 h at a pressure up to 20 bar. This will lead to a further cross-linking of the ORMOCER® material, whereas it has to be mentioned, however, that both – ORMOCER® core and cladding – are simultaneously exposed to this treatment.

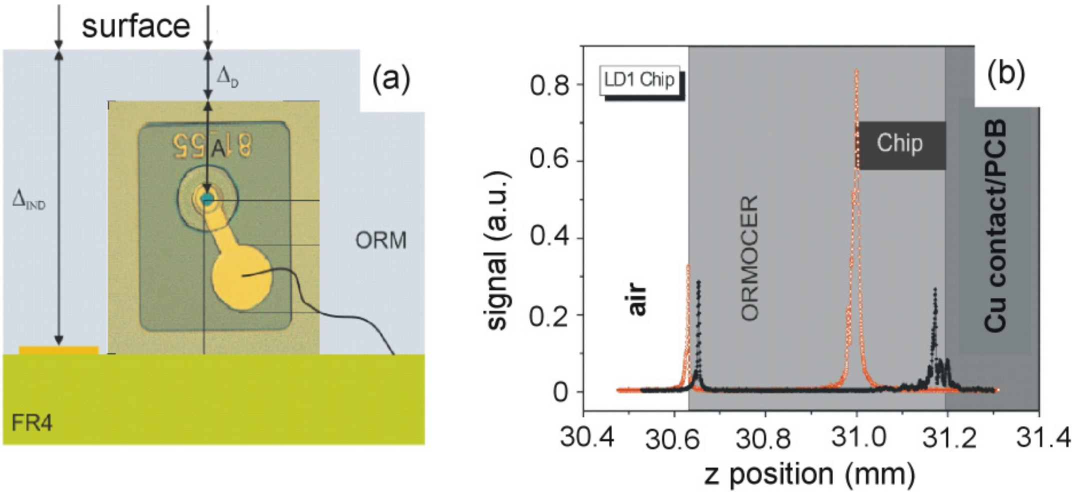

Figure 5 Principle of referencing the depth of the waveguide. (a) Sketch of the laser diode design as seen from the front side. (b) By means of a confocal optical setup, the intensity of the reflected light from the ORMOCER®/air interface (black line) and from the top edge of the laser diode chip (red line) is recorded as a function of the laser focus' z position (vertical direction in the figure).

While the absorption of optical polymers at 850 nm can be as low as for ORMOCER® materials, these low absorption values are often not achieved in produced polymer waveguide devices on PCB [24]. The reason can be found in the very rough PCB surfaces which easily amount to several 10 µm, in the wall roughness of the fabricated polymer waveguides as well as in possible scattering centers within the material itself. However, the wall roughness of the fabricated waveguides is highly important for efficient light-guiding, and they have to be in the lower nm regime. For avoiding an increased optical loss by the waveguide structure, their wall roughness should be at least lower than $\lambda/10$ of the wavelength used for data transfer. In the present case, this means that the roughness should be much lower than 85 nm. Recently, it was demonstrated using conventional UV lithography for the preparation of multimode ORMOCER® layers on PCB substrates that the loss values of the completely processed devices can be as low as the loss values for the pure material, and is about 0.05 dB/cm at 850 nm [25].

The refractive indices of the TPA-fabricated waveguides were characterized by the refracted near-field (RNF) method. Dependent on the TPA processing parameters, refractive indices of about 0.002 before and of about 0.0015 after thermal curing at 200 °C for 2 h were achieved. Even with this low index difference, data transport of 1 to 3 Gbit/s could be demonstrated at bit error rates (BER) as low as 10^{-12}, whereas an exchange of the emitter and introducing an electrical low-pass filter into the characterization equipment has yielded data transfer rates as high as 5 Gbit/s, but with a higher BER of about 10^{-9} [23,26,27]. It should be mentioned, however, that much higher values could be achieved with other material/initiator modifications which will be published elsewhere.

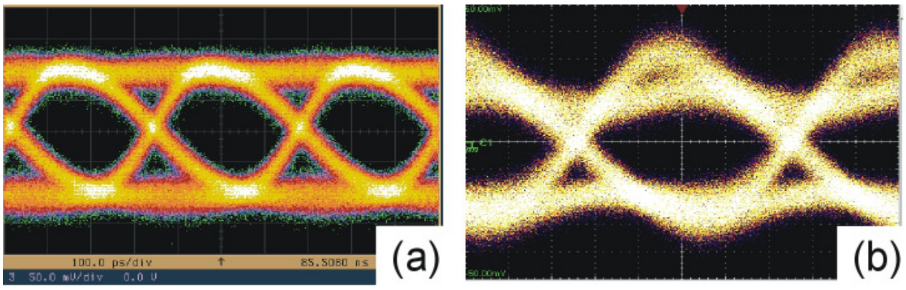

Figure 6 Eye diagrams of integrated optical connections with TPA-written ORMOCER® waveguides on a PCB substrate: (a) Before, and (b) after lamination at 200 °C for 2 h and 12 bar. The data transfer rates are (a) 3 and (b) 1 Gbit/s.

The resulting waveguides are as long as 12 cm. Dependent on the design, they exhibit a total attenuation of about 10 dB at 850 nm for the setup laser diode/ORMOCER® waveguide/photo diode, i.e. including the coupling losses at the two interfaces of the waveguides and the optoelectronic components. Figure 6 shows two eye diagrams before and after the lamination process at 200 °C for 2 h and 12 bar. The data transfer rate directly after the fabrication of the waveguides, i.e. before applying the harsh PCB production conditions of elevated temperature and pressure, is as high as 3 Gbit/s (Figure 6 (a)). Contrary to organic polymer materials commonly used for waveguide fabrication, which do not fulfill the harsh requirements of the PCB production process, the developed ORMOCER® system has fulfilled some major compatibility tests of the PCB production process such as being laminated at elevated temperatures for a couple of hours, the ability of being soldered, laser drilled for the fabrication of µ-vias and, finally, of being chemically processed (roughening, etching) without destruction of the resulting optical structures and layers. In Figure 6 (b), an eye diagram for ORMOCER® waveguides after lamination is shown, corresponding to a data transfer rate of still 1 Gbit/s.

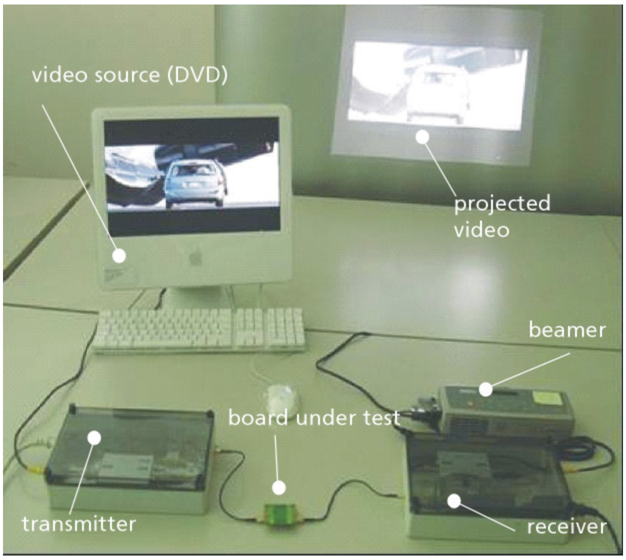

Figure 7 Data transmission of a movie via an optoelectronic PCB test-board with TPA-written ORMOCER® waveguides.

The data transfer rates achieved so far are sufficiently high to transfer a complete video signal with a data rate of 270 Mbit/s from a DVD via the emitter electronics across an optoelectronic PCB test-board with hybrid polymer waveguides and receiver electronics to a beamer and a screen (Figure 7).

IV. SUMMARY AND OUTLOOK

An integration concept for the realization of a direct optical integration into PCB was presented, which has addressed three major aspects: a pre-configured sub-mount of opto-electrical emitter and receiver onto the inner layers of a PCB, the development of a novel optical ORMOCER® material which is adapted to the TPA process, and the fabrication of waveguides in this ORMOCER® material by TPA-writing. It has to be mentioned that only one material is necessary to form the optical waveguide, i.e. the TPA-exposed material forms the waveguide's core, while the surrounding non-exposed material forms the cladding. With this procedure, the number of process steps for fabrication of waveguides on PCB could be significantly reduced, whereas also no solvent-based processes are necessary to fabricate the waveguides. With TPA-written waveguides data transfer rates as high as 4.8 Gbit/s at an emission wavelength of 850 nm were achieved. The major PCB compatibility tests were fulfilled by the novel inorganic-organic hybrid polymer material.

Additional work is still in progress in order to further optimize the hybrid polymer material systems in order to increase their response to the laser light and to control the organic cross-linking properties, resulting directly into higher index steps before and after the high temperature and high pressure lamination process. This will enable highly integrated optical designs with lower critical radii of curvatures such as, for example splitters. A comprehensive understanding of light-matter interaction processes in the TPA process will further support the refractive index increase. Further on, the optoelectronic devices have to be continuously developed in order to account for an improved assembly with a high degree of design tolerance for low-cost production.

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