Invited paper

Optoelectronic printed circuit board: 3D structures written by two-photon absorption

R. Houbertz*, V. Satzinger[a], V. Schmid[a], W. Leeb[b], and G. Langer[c]
Fraunhofer ISC, Neunerplatz 2, 97082 Würzburg, Germany
[a]Institute of Nanostructrured Materials and Photonics NMP, Joanneum Research, Franz-Pichler-Str. 30, A-8160 Weiz, Austria
[b]Vienna University of Technology, Gusshausstrasse 25/389, A-1040 Wien, Austria
[c]Austria Technologie & Systemtechnik, Fabriksgasse 13, A-8700 Leoben, Austria

*to whom correspondence should be addressed

ABSTRACT

The integration of optical interconnects in printed circuit boards (PCB) is a rapidly growing field due to a continuously increasing demand for high data rates, along with a progressive miniaturization of devices and components. For high-speed data transfer, materials and integration concepts are searched for which enable high-speed short-range connections, accounting also for miniaturization, and costs. Many concepts are discussed so far for the integration of optics in PCB: the use of optical fibers, or the generation of waveguides by UV lithography, embossing, or direct laser writing. Most of the concepts require many different materials and process steps. In addition, they also need highly-sophisticated assembly steps in order to couple the optoelectronic elements to the optical waveguides.

An innovative approach is presented which only makes use of only one individual inorganic-organic hybrid polymer material to fabricate optical waveguides by two-photon absorption (TPA) processes. Particularly, the waveguides can be directly integrated on pre-configured PCB by *in situ* positioning the optical waveguides with respect to the mounted optoelectronic components by the TPA process. Thus, no complex packaging or assembly is necessary, and the number of process steps is significantly reduced, where the process fits ideally into the PCB fabrication process. The material properties, the TPA processing of waveguides, and the integration concept will be discussed. Recent experiments employing vertical-cavity surface-emitting lasers demonstrated data rates exceeding 6 Gbit/s.

KEYWORDS

Inorganic-organic hybrid polymer, optical integration, two-photon absorption, optoelectronic printed-circuit board, high-speed interconnection, data transfer, multi-mode waveguide, 3D laser lithography

1. INTRODUCTION

The continuous increase in performance of microelectronic devices is also associated with a demand for optical interconnects to realize high data transfer rates. The trend to miniaturized devices continuously proceeds while, simultaneously, their complexity and functionality is continuously increasing. During the last decades, optical data transfer has revolutionized information and communication technologies. Integrated optical devices are the key components in current and future data transfer technologies, particularly on board level. Optical data transfer in general is highly superior to electrical data transfer with respect to data rate, transmission distance, bandwidth-length product, electromagnetic interference resistance, and weight.[1-3] Besides, optical packaging technology also enables a very high integration compared to copper wire systems, i.e. a higher physical interconnect density. This enables a continuous miniaturization of devices and, particularly, is thus very attractive for mobile applications.

The integration of optical elements into PCBs enables the substitution of many copper lines without any shielding measures. This is of particular interest since conventional copper technology faces severe limitations, for example related to an increase in cross-talk upon further reducing the packaging density of electrical connections. The high demand of bandwidth will push optical data connections further forward[3-5]. This particularly includes optical data transfer concepts in printed circuit board (PCB) technology, where complex and costly shielding as required for purely electrical concepts will not be necessary.

The fabrication of optical data transfer systems integrated into electrical PCBs, henceforth referred to optoelectronic PCB, is discussed for a long time. Their realization requires materials which enable the fabrication of optical waveguides with low absorption losses at the signal transmission wavelength. Additionally, the optical materials have to be completely compatible to the harsh PCB production requirements.

Most of the integration approaches on board level are employing hybrid approaches, where glass or polymer fibers[6], or polymer waveguides[7] are used, which are fabricated and integrated on PCBs by complex procedures. Optical backplanes based that are already commercially available, but they are expensive. Various technologies enabling low-cost fabrication of polymer waveguides are reported in the literature, among which are photo-lithography[8], laser ablation[9], embossing[10], or laser-direct writing[11]. These technologies all have in common that they require many different, cost-intensive process steps. Beside optical waveguide production, the integration of the waveguides on board level including light-coupling into and from the waveguides still is a matter of intensive investigations. Conventionally, this is often performed via more or less complex integration of mirrors, gratings, prisms or lens systems into the systems (see, e.g.,[7,9]). For a low-coat approach, organic polymers are often used as waveguide materials[12]. However, their performance on PCBs is often poor, and the fabrication of optical structures such as waveguides on PCBs is restricted to a few materials and technologies (see, e.g.[19-28]). In addition, the connection of electro-optical components such as lasers and photodiodes to the waveguide is very complex, thus resulting in high costs. As optoelectronic devices emitters such as, for example, vertical cavity surface emitting lasers (VCSEL) are employed which, for example, work at a wavelength of 850 nm, while photodiodes are used as receivers.

Motivation, technical approaches, and materials for optical interconnects at the board level can be found in numerous papers and books[13-15,29-31]. Among others, optical waveguides on PCB substrates were investigated by Moisel et al[16], Hartmann et al.[17], and Robertsson et al.[18]. Crucial points for the implementation of optical interconnects are the following. The space for optical circuit elements has to be minimized; optical waveguide layer fabrication should ideally be directly integratable into the PCB fabrication process, and materials compatible with existing PCB materials and processes should be used. Furthermore, a tradeoff has to be made between coupling losses, integration and fabrication costs. In order to reach reasonable goals, waveguide losses should not exceed
0.2 dB/cm[17].

Although the realization of optical waveguides is not a challenge anymore, there are two major challenges which are not yet solved satisfactorily: the performance of the optical polymer waveguides, and the active or passive alignment of the opto-electronic components relative to the waveguides. Very recently, a novel approach was proposed, combining a special inorganic-organic hybrid polymer with TPA patterning on pre-configured PCB substrates[32,33]. This concept particularly avoids complex packaging and assembly steps by a direct integration of optical connections on the internal layers of a PCB.

In the following, the realization of an integrated optical interconnection system into PCBs is described. The results will be discussed with respect to the underlying inorganic-organic hybrid polymer material class and the TPA technology. The resulting data transfer rates demonstrate the feasibility of the addressed concept.

2. EXPERIMENTAL

2.1 Inorganic-organic hybrid polymers

2.1.1 General aspects

Inorganic-organic hybrid polymers such as, for example ORMOCER®s[34], are class-II hybrid materials, i.e. inorganic and organic parts are covalently bonded[35]. They are synthesized via catalytically controlled hydrolysis/polycondensation reactions. By using alkoxysilanes, an organically modified inorganic-oxidic network is established on a molecular level[36]. By variation of alkoxysilane precursors and/or synthesis conditions such as, for example, reaction temperature, catalyst, or solvent, storage-stable resins with negative resist behavior can be synthesized. This particularly allows one to develop custom-designed materials for a large variety of applications, among which are ORMOCER®s for microsystem technology (MST). They are applied as optical interconnects or waveguides[37,38], for microoptics[39,40], in electro-optical applications[41], as dielectric layers[42], and as passivation materials for the encapsulation of microelectronic devices and components[43,44].

For application in MST, the processing of an ORMOCER® typically consists of two steps: (1) An establishment of an organically modified -[Si-O-Si]$_n$- structure via chemical syntheses, whereas the individual oligomers are in the range of 0.7 to 10 nm, present as a pre-polymer sol. As organic moieties, (oligo-)methacryl or acryl, styryl, or epoxy groups are often used. (2) A processing by various possible technologies in order to organically cross-link the organic moieties photochemically and/or thermally induced in order to build up the final inorganic-organic network.

As already mentioned, the material properties can be adjusted with respect to application and/or technology requirements. For example, for near infra-red (NIR) optics Si-OH groups present in the resin or the lacquer can be reduced with silylating agents. By multi-nuclei 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. The Young's modulus as well as the mechanical and thermal stability can be increased by increasing the inorganic content in the hybrid network. This simultaneously leads to a reduction of the coefficient of thermal expansion (CTE). By significantly reducing the Si-OH content and by increasing the inorganic content, the optical losses in the NIR regime can be reduced. This is due to the fact that Si-OH which absorbs at about 1438 nm (2nd harmonic)[45] is removed from the material, while the content of SiO_x which intrinsically has a low optical loss is increased. 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 organically polymerizable groups are also chosen with respect to application and/or technology requirements. For example, for patterning via UV or laser lithography, (oligo-)methacryl, acryl, or styryl moieties are usually chosen. If screen-printing is used for patterning, 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 can reduce the degree of polymerization due to sterical reasons, thus resulting in a reduced density within the coated layers. This, for example, directly influences the optical or dielectric properties such as the refractive index or the dielectric permittivity.

In order to account for highest processing flexibility, solvents formed upon synthesis are usually removed from the final resin under reduced pressure. This allows the user to replace them by other solvents for thin-film application for adjusting the material's viscosity. The storage stability with and without photo-initiators at room temperature was characterized for selected ORMOCER® material systems to be more than two years.

2.1.2 Characterization of the **ORMOCER®** *material*

An acrylate-modified inorganic-organic hybrid material (henceforth referred to as ORMOCER®-A1) was synthesized which is used for the fabrication of optical waveguides on PCBs by TPA. The photochemical reactivity of acrylate groups in the TPA process if formulated with suitable initiatiors is much higher than those compared to methacryl or styryl groups. In order to account for layer thicknesses up to 500 µm, no solvent was used for adjusting the viscosity. The material was modified such that the response to the femotsecond laser pulses is very high in order to achieve a high densification of the laser light-exposed areas. Several chromophore systems were used to initiate the organic cross-linking by TPA. However, the two-photon absorption cross-section of these chromophores differs significantly, being as low as approx. 10^{-55} cm^4s for 2-benzyl-2-dimethylamino-4'-morpholinobutyrophenone[46], or as high as $1250 \cdot 10^{-50}$ cm^4s/photon[47,48].

The optical loss of ORMOCER®-A1 resin was determined by UV-VIS spectroscopy to be about 0.02 dB/cm at a wavelength of 850 nm. The refractive index of the resin is approx. 1.491 (at 587 nm), while it can be as high as 1.523 ± 0.001 (at 635 nm) for the UV-exposed and subsequently thermally cured samples, resulting in a theoretically possible index difference of approx. 0.03 at a wavelength around 600 nm within one material.

2.1.3 Two-photon absorption

Two-photon absorption (TPA) processing was used for the fabrication of multimode waveguides using only ORMOCER®-A1 as waveguide material without any complicated further processing[49]. A pulsed femtosecond laser (center wavelength $\lambda = 800$ nm, pulse durations between 130 and 150 fs is focused into the ORMOCER®-A1 layer which was previously coated onto the PCB substrates. The material's absorption at the laser wavelength is low enough, thus enabling the fabrication of structures with high precision deep below (between 80 and 250 µm) the layer's surfaces. The photon density within the focal volume is high enough to initiate an organic cross-linking of the acrylate groups. This results in solid structures embedded in the non-exposed, thus low-viscosity ORMOCER®-A1 resin. The final waveguide is subsequently obtained by thermally treating the samples for 2 h at 200 °C in a nitrogen atmosphere (cf., section 3.2). This particularly avoids any solvent-based processing which also can be used for ORMOCER® patterning, for example for photonic crystal-like structures[50].

3. RESULTS AND DISCUSSION

3.1 Concept of the optoelectronic PCB

The proposed concept addresses three major aspects, whereas emphasis was on a significant reduction in process steps and thus costs (cf., section 3.2):

1. The optoelectronic components (transmitter, receiver) should be directly mounted on the PCB's internal layers (pre-configuration),
2. 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, should be employed to demonstrate the feasibility of this concept, and
3. the optical waveguide fabrication by TPA should be possible without any solvent-based processes, i.e. it should take place in only one individual ORMOCER® material, constituting waveguide core and cladding at the same time.

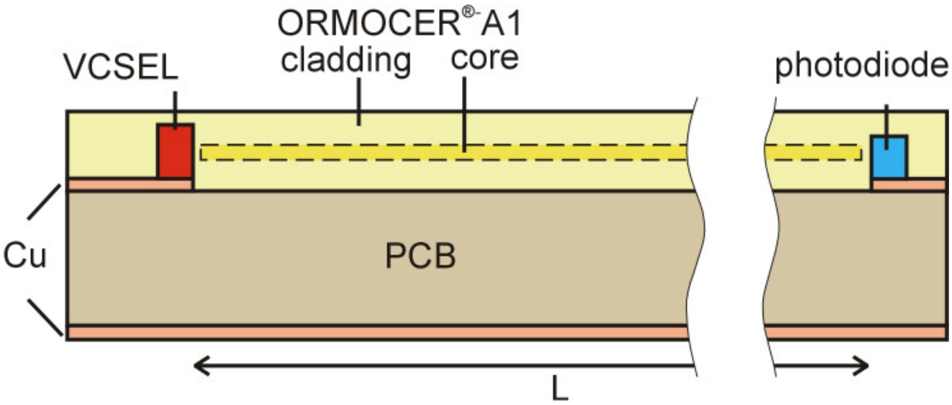

Figure 1. Integration concept of an optoelectronic PCB.

Figure 1 shows a schematic sketch of the integration concept. It is based on the complete embedding of transmitter and receiver into the ORMOCER®-A1 resin, which simultaneously protects mounted optoelectronic components. In addition, the configured PCB can be thinner than for other integration concepts due to the fact that no complicated assembly to attach the optoelectronic components to the optical waveguide structures is necessary, and that the optoelectronic components are mounted on the inner layers of the PCB. The waveguides are subsequently fabricated with highest precision by TPA, and they are directly routed to the optoelectronic component's active facets.

3.2 Waveguide processing

Compared to UV lithography, TPA processing allows one to directly create computer-generated 3D structures at very high speed. This particularly reduces the necessary process steps for waveguide fabrication, firstly by choice of the material, and secondly by choice of the fabrication method. Figure 2 shows typical process flows of the underlying processes for UV and TPA experiments for fabrication of an optoelectronic PCB.

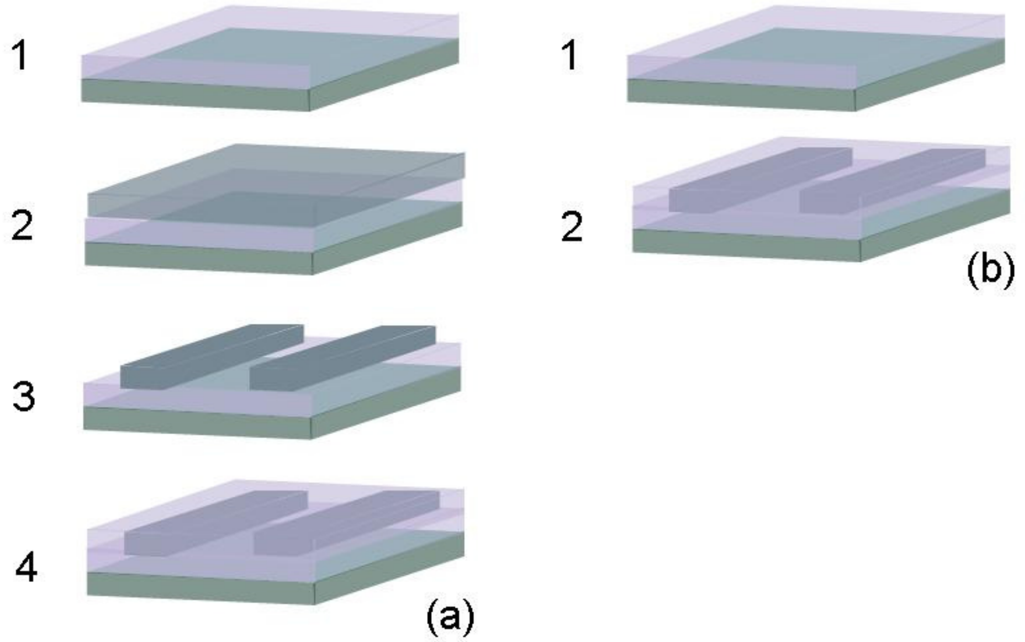

Figure 2. Process flow chart of optoelectronic PCB fabrication by (a) UV lithography, and (b) TPA processing. In (a) steps 2, 3, and 4 consist of a series of different process steps (see text). In (b), step 2 consists of a registration of the optoelectronic components and the optical material's surface, waveguide formation by TPA, and further thermal treatment (PCB production).

As obvious from Figure 2, the preparation of optical interconnects on board level via UV lithography requires much more process steps and material resources than the proposed concept making use of TPA processing. For the materials available so far, approx. 9 to 17 different process steps have to be carried out. These include, for example sample cleaning and coating procedures, where sometimes primers are necessary to promote the adhesion between the substrate and the organic waveguide material, pre- and post-exposure bake steps, UV exposure of the cladding and the core layers, respectively, thermal curing steps, and reactive ion etching for some materials. For example, for a standard process for ORMOCER® waveguides, two different ORMOCER® materials with different refractive indices are necessary which form the cladding and the core layer. Dependent on the substrate and the waveguide material, 9 to 13 different process steps are typically employed. Contrary to conventional waveguide fabrication by UV lithography, the fabrication of waveguides via the TPA process using ORMOCER®-A1 significantly reduces production costs and time compared to etching and conventional UV lithography processes. The sample is coated with the ORMOCER® material, whereas usually no adhesion promoter is used in this process. The waveguide is subsequently inscribed into the material with the femtosecond laser. Final process step is a thermal curing process, resulting in only 3 to 4 process steps, whereas the latter already belongs to a PCB production step.

Moreover, this technique allows one to vary the waveguide's shape and size by simply modifying the laser focus (cf., Figure 3). Besides, the combination of pre-configured PCB, ORMOCER®-A1, and TPA processing saves resources (e.g., solvents, energy), and thus also costs.

The waveguide preparation is influenced by many different process parameters. It could be shown that, beside laser parameters such as power, number of applied pulses, and irradiation time, the structures are also influenced by the laser wavelength[51]. 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®-A1 system, reliable functional waveguide structures can be produced in one material far beyond the initiator's highest cross-section.

Prior to the waveguide fabrication, appropriate processing parameters for the laser light/ORMOCER® interaction have to be found. Screening experiments of laser power or feed rate of the sample motion were performed, yielding a parameter range suitable for initiating the organic cross-linking of ORMOCER®-A1 without damaging the material. The average laser power can range between 80 and 250 µW, where ORMOCER®-A1 waveguides can be produced with a good index contrast without damaging the material, while the surrounding non-exposed material forms the cladding layer (Figure 3).

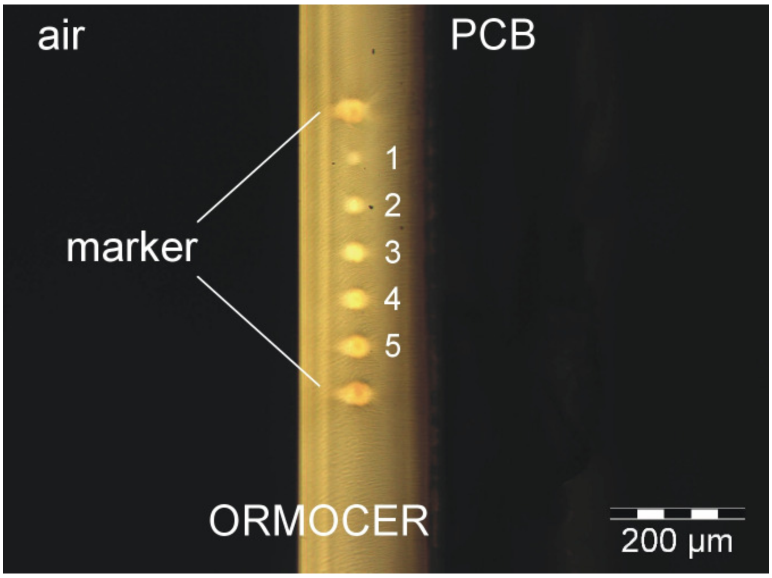

Figure 3. Cross-section (optical microscopy) of a TPA-patterned ORMOCER®-A1 layer on a PCB substrate. The white spots correspond to the waveguide cores. Markers were written at 270 µW average laser power, while the waveguides were fabricated with 170 (1), 190 (2), 210 (3), 230 (4), and 250 µW (5).

The dimensions of the pre-configured PCBs were 5 x 5, 10 x 5, or 15 cm x 5 cm. The boards are equipped with 850 nm VCSELs that are mounted upright on the die edge such that the emitting area of the VCSEL points towards a photo-diode. After a rough cleaning of the board, the

ORMOCER® is drop-casted on the PCB substrate, and a soft-bake on a hotplate is carried out. Finally, a UV flood exposure in an Ar atmosphere is performed in order to mechanically stabilize the material.

Before focussing the TPA laser into the material and waveguide patterning, a precise 3D registration of the sample is required in order to align the waveguide relative to the active facets of the optoelectronic components. The lateral gauging of the chips, i.e. their x-y position is determined with a CCD camera placed next to the microscope objective. Thus, the positions of the laser- and the photo-diode are registered, the waveguide design is defined, and the ORMOCER®-A1 surface along the waveguide path is mapped by monitoring the intensity of the back-reflected light of a He-Ne laser with a photo-diode in a confocal setup. The latter method is also used to determine the z-position of each optoelectronic component that is attached to the PCB substrate (Figure 4). Out of this, the start and end point and the path of the waveguide within the ORMOCER® layer can be defined. The precise 3D registration of the sample is important since otherwise a misalignment of the waveguide and the optoelectronic components would occur, resulting in an inefficient light-coupling into and out of the waveguides. This would increase the optical losses, and thus lead to either a larger number of bit errors or a reduction of the maximum data rate.

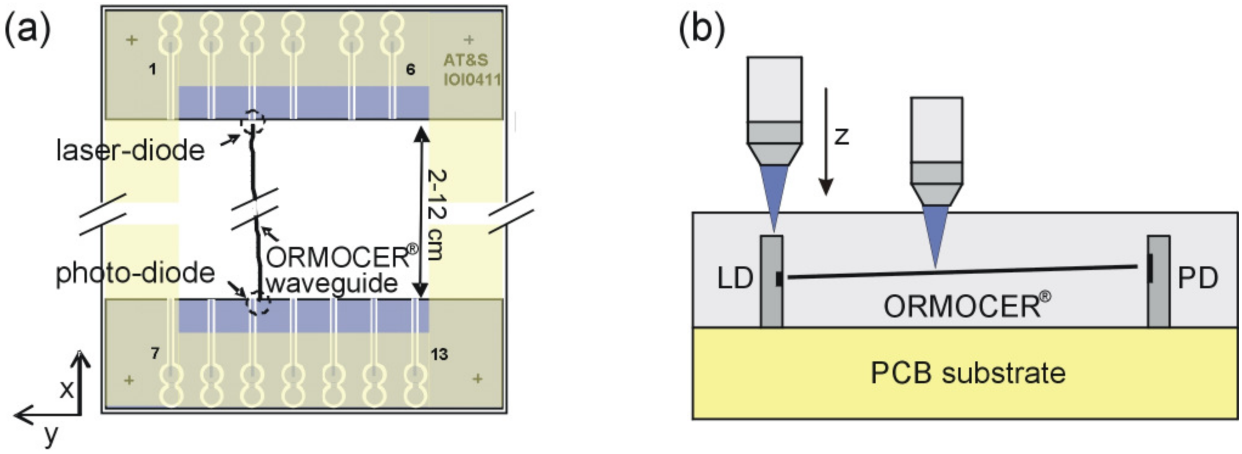

Figure 4. (a) Layout of an optoelectronic PCB with mounted laser and photodiode and an ORMOCER®-A1 waveguide as integrated optical interconnect. (b) Fabrication principle of an embedded waveguide, written by TPA lithography.

Taking into account the measured x, y and z coordinates of the optoelectronic components and the ORMOCER®-A1 surface profile, the start and end point and the path of the waveguide within the ORMOCER® layer can be defined. Subsequently, the laser focus is scanned across the optical layer in order to form a direct optical interconnect between the laser and photodiode. The writing of the waveguide takes approx. 1 to 6 minutes, depending on the dimensions of the PCB board, and thus on the length of the waveguide. During the TPA process, the laserdiode is operated in order to continuously measure the photocurrent of the photodiode. This enables one to monitor online the increase of the light-induced current of the photodiode at each point of the proceeding waveguide.

The refractive indices of waveguide core and cladding were characterized by refractive near-field (RNF) measurements before and after thermally curing the samples at 150 °C for 3 h in ambient atmosphere or at 200 °C for 2 h in an N_2 atmosphere which simulates a process step in the PCB production. The annealing rates were about 1 and 5 K/min. Dependent on the material formulation and further treatment, refractive index differences of up to approx. 0.005 were achieved. This index difference already allows one to fully utilize the 3D capabilities of the two-photon lithography, which not only permits the fabrication of individual embedded waveguides with a simple geometry, but also enables more complex waveguide structures such as waveguide bundles[49] with largely arbitrary waveguide configurations or curved waveguides.

3.3 Data transfer

Using the concept, material, and patterning method described above, various optoelectronic PCBs were fabricated, and their data transmission capability was determined. The following recent results were obtained with a PCB where an optical waveguide of 7 cm in length was written.

As transmitter laser, a commercially available longitudinally multi-mode VCSEL diode emitting at a wavelength of $\lambda = 850$ nm (type ULM850-05-TN-U0101U, ULM Photonics) was used. At room temperature, the laser DC output power is about 2 mW, if driven with a current of 6 mA. At this operating point, the transverse mode is doughnut-shaped, and the beam which is emitted from an area of some 10 µm diameter has a full $1/e^2$ beam divergence of approx. 18 mrad. For simple non-return-to-zero on-off-keying, the device is specified for data rates up to 5 Gbit/s. The GaAs pin photodiode acting as a receiver (type ULMPIN-04-TN-U0101U, ULM Photonics) has a sensitive area of 100 µm in diameter, and allows the demodulation of data rates up to 4.3 Gbit/s, if it is biased at -2 V. Its DC sensitivity at 850 nm was determined to be 0.6 A/W. Laser and photodiode were mounted onto a PCB, and short 50-Ω strip lines were provided for an electrical connection to SMA plugs. Laser and photodiode are embedded in the ORMOCER®-A1 layer, into which the core of the optical waveguide was inscribed (cf., Figure 3). Its cross-section had an effective diameter of approx. 30 µm. The end caps of the waveguide are separated from the optoelectronic devices about 10 µm. The entire board was thermally cured prior to the high-frequency characterization.

For an optoelectronic PCB, the properties of primary interest are the optical losses and the upper limit of the data rate for a specified bit error ratio. There are several sources for optical losses. They may be caused by the laser-waveguide interface, by optical absorption of the waveguide material, by scattering losses in case of inhomogeneities or rough waveguide walls, and by imperfect waveguide-to-photodiode coupling. Since the dependence of laser output power on the temperature is known, and the DC photocurrent vs. temperature was determined, the total optical loss and its temperature dependence could be estimated. If the temperature is increased from 0 to 80 °C, the losses decreased steadily from 5 dB to a value as low as 1 dB.

For measuring the bit error ratio (BER) as a function of the data rate R, a pseudo-random-bit-sequence of length 2^{31}-1 with a peak-to-peak modulation voltage of $V_{pp} = 385$ mV to the laser bias of $I = 6$ mA was added. The signal received by the photodiode was amplified by a baseband amplifier with a noise figure of 2.7 dB. Figure 5 shows the results at a temperature of 27 °C. From the dashed horizontal line, it can be determined that a data rate of almost 7 Gbit/s can be transmitted, while still obtaining an acceptable transmission quality (bit error ratio) of BER = 10^{-9}.

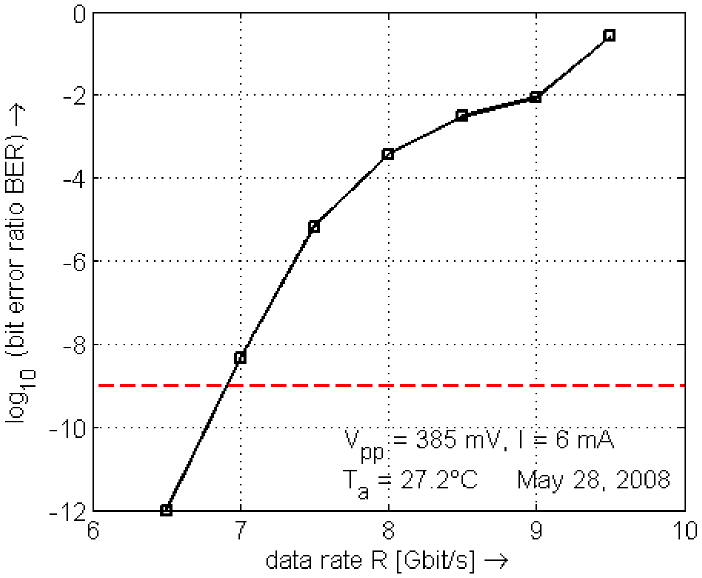

Figure 5. Bit error ratio (BER) vs. data rate (R) for an optoelectronic PCB with an ORMOCER®-A1 waveguide of 7 cm in length.

4. CONCLUSIONS

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 a laser and a photodiode onto the inner layers of a PCB, a novel optical ORMOCER® which is adapted to the TPA process in order to form waveguide core and cladding in just one material, and the fabrication of waveguides by TPA lithography. Thus, the number of process steps for waveguide fabrication on PCB is significantly reduced compared to conventional materials and processing technologies, whereas also no solvent-based processes are necessary. Data transfer rates as high as 7 Gbit/s at a bit error ratio of about 10^{-9} were achieved on thermally cured PCBs. The major PCB compatibility tests were fulfilled by the novel inorganic-organic hybrid polymer material.

5. ACKNOWLEDGEMENTS

The authors would like to thank C. Cronauer and A. Martin for their excellent technical assistance in ORMOCER® synthesis, processing, and characterization, and H. Wolter (Fraunhofer ISC) and M. Riester (marisTechCon) for fruitful discussions. Ch. Wächter (Fraunhofer IOF) is greatfully acknowledged for the RNF measurements, and G. Schmid (Vienna University of Technology) for data transmission measurements. Part of this work was performed in a research and development project of AT&S which is funded by the Austrian NANO Initiative.

6. REFERENCES

[1] B. Lunitz, J. Guttmann, H.-P. Huber, J. Moisel, and M. Rode, *Experimental demonstration of 2.5 Gbit/s transmission with 1 m polymer optical backplane*, Electron. Lett. **37**, 1079 (2001).

[2] C. Berger, M. A. Kossel, C. Menolfi, T. Morf, T. Toifl, and M. L.Schmatz, *High-density optical interconnects within large-scale systems*, Proc. SPIE **4942**, 222 (2003).

[3] Y. Li, *What ultimately limits capacity and connectivity in optical interconnects?*, *Proc. 2nd Int. Workshop Massively Parallel Processing Using Optical Interconnections*, 1995, pp. 203.

[4] R. Cutler, *Challenges for achieving 10 Gbps copper backplanes*, Electron. Eng. **73**, 41 (2001).

[5] M. Feldman, S. Esener, C. Guest, and S. Lee, Comparison between optical and electrical interconnects based on power and speed characteristics, Appl. Opt. **27**, 1742 (1988).

[6] K. Vandeputte, P. Van Daele, E. Hoedt, J. Van Koetsem, and J. Hossfeld, *Low cost multi-fiber add/drop multiplexer demonstration system*, Proc. of the 25th European Conference on Optical Communication, Nice, Vol. **1,** 112 (1999).

[7] H. Schröder, J. Bauer, F. Ebling, M. Franke, A. Beier, P. Demmer, W. Süllau, J. Kostelnik, R. Mödinger, K. Pfeiffer, U. Ostrzinski, and E. Griese, *Waveguide and packaging technology for optical backplanes and hybrid electrical-optical circuits,* Proc. SPIE Vol. **6124**, 612407-13 (2006).

[8] J. Kobayashi, T. Matsuura, Y. Hida, S. Sasaki, and T. Maruno, *Fluorinated Polyimide Waveguides with Low Polarization-Dependent Loss and Their Applications to Thermooptic Switches*, J. Lightwave Techn. **16**, 1024 (1998).

[9] G. Van Steenberge, P. Geerinck, S. Van Put, J. Van Koetsem, H. Ottevaere, D. Morlion, H. Thienpont, and P. Van Daele, *MT-Compatible Laser-Ablated Interconnections for Optical Printed Circuit Board*, J. Lightwave Techn. **22**, 2083 (2004).

[10] E. Griese, *A high-performance hybrid electrical-optical interconnection technology for high-speed electronig systems*, IEEE Trans. Adv. Packaging **24**, 375(2001).

[11] F. Tooley, N. Suyal, F. Bresson, A. Fritze, J. Gourlay, A. Walker, and M. Emmery, *Optically written polymers used as optical interconnections and for hybridization*, Opt. Mat. **17**, 235 (2001).

[12] L. Eldada, *Nanoengineered polymers for photonic integrated circuits*, Proc. of SPIE **5931**, 59310F-1 (2005).

[13] M. Forbes, J. Gourlay, and M. Desmulliez, *Optically interconnected electronic chips: A tutorial and review of the technology*, Electron. Commun. Eng. J. **13**, 221 (2001).

[14] H. Schröder, N. Arndt-Staufenbiel, M. Cygon, and W. Scheel, *Planar glass waveguides for high performance electrical-optical-circuit-boards (EOCB)—The glass-layer-concept*, Proc. 53rd Electronic Components and Technology Conf., 1053 (2003).

[15] Y. Ishii, S. Koike, Y. Arai, and Y. Ando, *SMT-compatible optical-I/O chip packaging for chip-level optical interconnects*, Proc. 51st Electronic Components and Technology Conf., 870 (2001).

[16] J. Moisel, H.-P. Huber, J. Guttmann, O. Krumpholz, B. Lunitz, M. Rode, and R. Schoedlbauer, *Optical backplane*, 27th European Conf. Optical Communication **3**, 254 (2001).

[17] D. H. Hartman, G. R. Lalk, J. W. Howse, and K. R. R, *Radiant cured polymer optical waveguides on printed circuit boards for photonic interconnection use*, Appl. Opt. **28**, 40 (1989).

[18] M. Robertsson, O. Hagel, G. Gustafsson, A. Dabek, M. Popall, L. Cergel, P. Wennekers, P. Kiely, M. Lebby, and T. Lindahl, *O/e-MCM packaging with new, patternable dielectric and optical materials*, Proc. 48th Electronic Components Technology Conf., 1413 (1998).

[19] R. Himmelhuber, M. Fink, K. Pfeiffer, U. Ostrzinski, A. Klukowska, G. Gruetzner, R. Houbertz, and H. Wolter, *Innovative materials tailored for advanced microoptic applications*, Proc. of SPIE **6478**, 64780E (2007).

[20] H. Schröder, J. Bauer, F. Ebling, and W. Scheel, *Polymer optical interconnects for PCB*, Proc. Polytronic, Potsdam, Germany, 337 (2001).

[21] G. L. Bona, B. J. Offrein, U. Bapst, C. Berger, R. Beyeler, R. Budd, R. Dangel, L. Dellmann, and F. Horst, *Characterisation of parallel optical-interconnect waveguides*, Integration on a printed circuits board, Proc. SPIE **5453**, 134 (2004).

[22] A. W. Norris, J. V. Degroot, T. Ogawa, T. Watanabe, T. C. Kowalczyk, A. Baugher, and R. Blum, *High reliability of silicone materials for use as polymer waveguides*, Proc. SPIE **5212**, 76 (2003).

[23] A. Neyer, S. Kopez, and E. Rabe, *Lichtwellenleiter auf Silikon*, *Elektronik* **09** (2005).

[24] J. Kim, J. Kang, and J. J. Kim, *Simple and low cost fabrication of thermally stable polymeric multimode waveguides using UV-curable epoxy*, Jpn. J. Appl. Phys. **42**, 1277 (2003).

[25] Y. Ishii, S. Koike, Y. Arai, and Y. Ando, *SMT- compatible large-tolerance optobump interface for interchip optical interconnections*, IEEE Trans. Adv. Packaging **26**, 122 (2003).

[26] N. Keil, W. Wirges, H. H. Yao, S. Yilmaz, C. Zawadzki, M. Bauer, J. Bauer, and C. Dreyer, *Polymer optical waveguide devices for photonic networks*, Proc. VIII International POF Conference '99, Chiba, Japan, 217 (1999).

[27] H. Ma, A. K.–Y. Jen, and L. R. Dalton, *Polymer based optical waveguides: Materials, Processing, and Devices*, Adv. Mater. **14**, 1339 (2002).

[28] M. Stach, F. Mederer, R. Michalzik, B. Lunitz, J. Moisel, and D. Wiedemann, *10 GHz/s data transmission experiments over optical backplane waveguides with 850nm wavelength multimode VCSELs*, Proc. 7th Workshop Optics in Computing Technology, Mannheim, Germany, 47 (2002).

[29] K.-S. Lee, R. H. Kim, D.-Y. Yang, S. H. Park, *Advances in 3D nano/microfabrication using two photon initiated polymerization*, Prog. Polym. Sci. **33**, 631-681 (2008).

[39] Seung-Ho Ahn, In-Kui Cho, and Sang-Pil Han, *Demonstration of high-speed transmission through waveguide-embedded optical backplane*, Optical Engineering **45**, 085401 (2006).

[31] L. Schares, J.A. Kash, F.E. Doany, C.L. Schow, Ch. Schuster, D.M. Kuchta, P.K. Pepeljugoski, J.M. Trewhella, Ch.W. Baks, R.A. John, L. Shan, Y.H. Kwark, R.A. Budd, P. Chiniwalla, F.R. Libsch, J. Rosner, C.K. Tsang, C.S. Patel, J.D. Schaub, R. Dangel, F. Horst, B.J. Offrein, D. Kucharski, D. Guckenberger, S. Hegde, H. Nyikal, C.-K. Lin, A. Tandon, G. Trott, M. Nystrom, D.. Bour, M.R.. Tan, and D.W. Dolfi, *Terabus: Terabit/Second-Class Card-Level Optical Interconnect Technologies*, IEEE J. Sel. Top. Quant. Electron **12**, 1032 (2006).

[32] G. Langer and M. Riester, *Two-photon absorption for the realization of optical waveguides on printed circuit boards*, Proc. of SPIE **6475**, 64750X-1 (2007).

[33] V. Schmidt, L. Kuna, V. Satzinger, R. Houbertz, G. Jakopic, and G. Leising, *Application of two-photon 3D lithography for the fabrication of embedded ORMOCER® waveguides*, Proc. of SPIE **6476**, 64760P-1 (2007).

[34] Registered trademark of the Fraunhofer-Gesellschaft für Angewandte Forschung e.V., Germany.

[35] C. Sanchez, B. Julián, Ph. Belleville, and M. Popall, *Applications of hybrid organic–inorganic nanocomposites*, J. Mater. Chem. **15**, 3559 (2005).

[36] K.-H. Haas, and H. Wolter, *Properties of Polymer-Inorganic Composites*, Encyclopedia of Materials: Science and Technology **7584**, 1 (2001).

[37] S. Uhlig, L. Fröhlich, M. Chen, N. Arndt-Staufenbiel, G. Lang, H. Schröder, R. Houbertz, M. Popall, and M. Robertsson, *Polymer optical interconnects - a scalable large-area panel processing approach*, IEEE Trans. Adv. Packaging **29**, 158 (2006).

[38] U. Streppel, P. Dannberg, Ch. Wächter, A. Bräuer, L. Fröhlich, R. Houbertz, and M. Popall, *New wafer-scale fabrication method for stacked optical waveguide interconnects and 3D micro-optic structures using photoresponsive (inorganic-organic hybrid) polymers*, Opt. Mater. **21**, 475 (2002).

[39] A. Bräuer, P. Dannberg, G. Mann, and M. Popall, *Precise Polymer Micro-Optical Systems*, MRS Bull. **26**, 519 (2001).

[40] R. Houbertz, L. Fröhlich, M. Popall, U. Streppel, P. Dannberg, A. Bräuer, J. Serbin, and B.N. Chichkov, *Inorganic-Organic Hybrid Polymers for Information Technology: from Planar Technology to 3D Nanostructures,* Adv. Eng. Mater. **5**, 551 (2003).

[41] M.E. Robertsson, O.J. Hagel, G. Gustafsson, A. Dabek, M. Popall, L. Cergel, P. Wennekers, P. Kiely, M. Lebby, and T. Lindhal, *O/e-MCM Packaging with New, Patternable Dielectric and Optical Materials,* Proc. 48th Electron. Comp. Technol. Conf. (Seattle, Washington, USA), IEEE Catalogue No. 98CH36206, 1413 (1998).

[42] U. Haas, A. Haase, V. Satzinger, H. Pichler, G. Leising, G. Jakopic, B. Stadlober, R. Houbertz, G. Domann, and A. Schmitt, *Hybrid polymers as tunable and directly-patternable gate dielectrics in organic thin-film transistors*, Phys. Rev. **B 73**, 235339 (2006).

[43] R. Houbertz, L. Froehlich, J. Schulz, and M. Popall, *Inorganic-organic Hybrid Materials (ORMOCER®s) for Multilayer Technology - Passivation and Dielectric Behavior,* Mater. Res. Soc. Symp. Proc. **665**, 321 (2001).

[44] R. Houbertz, J. Schulz, L. Froehlich, G. Domann, and M. Popall, *Inorganic-organic hybrid materials for polymer electronic applications*, Mater. Res. Soc. Symp. Proc. **769**, 239 (2003).

[45] A. Rousseau, and B. Boutevin, *Proc. Of the Plastic Optical Fibrers Conference*, Paris (1992), p. 33.

[46] J. Serbin, A. Egbert, A. Ostendorf, and B. N. Chichkov , R. Houbertz, G. Domann, J. Schulz, C. Cronauer, L. Fröhlich, and M. Popall, *Femtosecond laser-induced two-photon polymerization of inorganic–organic hybrid materials for applications in photonics*, Opt. Lett. **28**, 301 (2003).

[47] B. H. Cumpston, S. P. Ananthavel, S. Barlow, D. L. Dyer, J. E. Ehrlich, L. L. Erskine, A. A. Heikal, S.M. Kuebler, I. Y. S. Lee, D. McCord-Maughon, J. Qin, H. Rockel, M. Rumi, X.-L. Wu, S. R. Marder, J. W. Perry, *Two-photon polymerization initiators for three-dimensional optical data storage and microfabrication*, Nature (London) **398**, 51 (1999).

[48] K. J. Schafer, J. M. Hales, M. Balu, K. D. Belfield, E. W. Van Stryland, D. J. Hagan, *Two photon absorbtion cross-sections of common photoinitiators*, J. Photochem. Photobiol. **A162**, 497 (2004).

[49] R. Houbertz, H. Wolter, V. Schmidt, L. Kuna, V. Satzinger, Ch. Wächter, and G. Langer, *Optical waveguides embedded in PCBs – a real world application of 3D structures written by TPA*, Mater. Res. Soc. Symp., Fall Meeting, Boston, USA (2008).

[50] R. Houbertz, P. Declerck, S. Passinger, A. Ovsianikov, J. Serbin, B.N. Chichkov, *Investigations on the generation of photonic crystals using two-photon polymerization (2PP) of inorganic-organic hybrid polymers with ultra-short laser pulses*, In „Nanophotonic Materials: Photonic Crystals, Plasmonics, and Metamaterials“ (R.W. Wehrspohn, H.S. Kitzerow, und K. Busch, Eds.), Wiley VCH, pp. 97-114 (2008).

[51] R. Houbertz, H. Wolter, P. Dannberg, J. Serbin, and S. Uhlig, *Advanced packaging materials for optical applications: bridging the gap between nm-size structures and large-area panel processing*, Proc of SPIE **6126**, 612605 (2006).