3D optical waveguides produced by two photon photopolymerisation of a flexible silanol terminated polysiloxane containing acrylate functional groups

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Abstract: Optical waveguides are becoming increasingly important in the developing area of broadband communications. The field of electronics is advancing rapidly, leading to further demands for larger data storage, smaller components and a better design of integrated optical circuits. The integration of optical interconnects on printed circuit boards (PCBs) requires precise technologies to make this emerging field possible. A promising new microfabrication technique, two-photon photopolymerisation (2PP) can be used to produce three dimensional structures in the sub-micron region. Near-infrared lasers can be used to create 3D optical waveguides by initiating the photopolymerisation of high refractive index monomers in polymeric matrix materials. Terminal silanol groups are intermediates for room temperature vulcaniseable (RTV) silicones and can be cross linked with functional silanes to produce flexible, transparent polymeric materials with high thermal stabilities. A silanol terminated polysiloxane; cross linked with a methyl substituted acryloxy silane has been developed as a suitable material for the fabrication of optical waveguides by two-photon absorption (TPA). A higher refractive index is achieved upon polymerisation of the acrylate functional groups. The material has been shown to be suitable in the fabrication of 3D optical waveguides with a high refractive index contrast. The cured material is fully flexible and exhibits high thermal stability and optical transparency. The material was characterised by Fourier transform infrared spectroscopy (FT-IR), simultaneous thermal analysis coupled with mass spectrometry (STA-MS) and near-infrared spectroscopy (NIRS). Waveguides were observed by phase contrast microscopy, cut back measurements and were additionally directly integrated onto specially designed PCBs by correctly positioning waveguide bundles between optoelectronic components using TPA.

OCIS codes: (190.0190) Nonlinear optics; (250.0250) Optoelectronics; (320.0320) Ultrafast optics

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1. Introduction

Polymer optical waveguides have attracted attention in recent years for applications in active and passive components for optical communication systems. Their ease of tuning, optical properties, relative low cost and processing capabilities deem them highly suitable for such

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applications [1]. Advances in electronics and improved performances of microelectronic devices have led to a greater demand in optical interconnects, able to realise high data transfer rates [2,3].

Integrated optical devices are the key components in future data transfer technologies, and enable the continuation of increased complexity, miniaturisation and functionality, particularly on board level [4]. Optical interconnects also enable high integration, leading to a decrease in the size of the devices needed. It is possible to exceed electrical data transfer using optical data transfer with respect to data rate, transmission distance, electromagnetic interference, resistance and weight [5]. With the substitution of copper lines; which are limited due to the increase in cross talk when the packing density of electrical interconnects is decreased, miniaturisation of components is made possible without the undesirable problems related to common copper circuits [6]. Optical waveguides commonly consist of a dielectric structure having a high refractive index surrounded by a lower refractive index cladding material. Light waves are guided by total internal reflection due to the waveguide core having a refractive index higher than that of the surrounding material.

Optoelectronic PCBs have to overcome a number of problems in relation to the processing, particularly the production requirements of the PCBs. The properties of the material therefore have to be suitable for this specific purpose. The material has to have low absorption losses in the telecom and datacom wavelengths. Both the core and the cladding material need to be optically transparent, as absorption is the dominant factor causing propagation losses in waveguides [7]. Other sources of these losses can arise from scattering, polarisation dependence, reflection and radiation [8]. The material must also have a high thermal stability in order to withstand processing steps at elevated temperatures. Optical interconnects have to be correctly positioned in relation to the polymeric waveguides for efficient light guiding to take place [9].

The use of polymeric optical waveguides is one way to avoid such problems associated with common electronic data transfer. Polymer optical waveguides have been investigated extensively as they are easily processed and can be integrated with electronic and optical devises. The commercial methods of producing optical waveguides on printed circuit boards include complex processes and steps, such as photo lithography, laser ablation, embossing, photoresist–based patterning and electrospinning techniques [10,11]. Two photon induced photopolymerisation is a modern technique, which is gaining interest as a method to fabricate sub-micron structures in suitable photopolymerisable resins [12]. The three-dimensional microfabrication method, carried out by using near infrared (NIR) lasers can produce 3D structures with spatial feature resolution down to 120 nm [13,14]. When focused into the volume of a photosensitive material, the laser pulses initiate polymerisation via two-photon absorption. Compared to one-photon absorption, two photon induced polymerisation occurs by the simultaneous absorption of two photons in a non-linear process by a photoinitiator. The generation of radicals is triggered because the energy of the absorbed photons fulfils the resonance requirement in the excited electronic state. The confinement of the excitation volume at the focal point of a pulsed laser can produce highly resolved objects. The production of sub-micron structures using this technique has demonstrated the potential of this application in optical devices and optical storage [15,16]. Another method used to laser structure polymers has also been successfully achieved recently via induced avalanche ionization, which achieves high resolutions and avoids the use of photoinitiators [17].

Polymeric materials are frequently chosen for such applications as they exhibit controlled refractive indices, are thermally stable and adhere well to a wide range of substrates. Other optical materials such as borosilicate glass and chalcogenides have also been investigated for suitable matrix materials however polymers are often chosen due to their inherent mechanical flexability [18]. Several optical polymers have been developed; including polymethylmethacrylate (PMMA), polycarbonate and epoxy resins [19]. Materials being developed for the use in optical polymer waveguide fabrication by TPA include flexible

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polydimethyl diphenyl siloxane matrices [20,21]. Similar materials consisting of polydimethyl siloxane matrices swollen by monomer mixtures, also possess good flexibility and optical properties [22]. A second type of material uses porous sol-gel materials based on tetramethoxysilane as precursor filled with acrylate monomers [23]. Another common class of materials developed and utilised as matrix materials for two photon photopolymerisation (TPP) are ORMOCERS® [24]. These types of acrylate modified inorganic-organic hybrid materials have been studied extensively for the fabrication of waveguides on PCBs by two photon processes [25].

Polydimethylsiloxane (PDMS) polymers offer a combination of properties including a low glass transition temperature (Tg) and high temperature, chemical and oxidation resistance. This has lead the material to be used for structuring of 3D microstructures and bio-scaffolds [26]. To take full advantage of these properties the polymer needs to be cross linked into a network. An important class of reactions used to cross link siloxanes is the condensation of silanol groups to form siloxane bonds, from silanol terminated PDMS. Silanol terminated PDMS polymers are the main components in one and two part sealant systems, used with small amounts of metal catalysts such as dibutyl tin dilaurate. Upon curing, the PDMS system can produce cross linked silicone films as well as flexible silicone elastomers. With the introduction of a tri or tetra functional molecule, a 3D network can be produced. Trialkoxysilanes (R`Si(OR``)3) when used as cross linkers, enable moisture curing upon exposure to air, with the alkoxy functionality hydrolysed to form silanol and the corresponding alcohol. The silanol then condenses with the Si-OH-terminated polymer, producing a cross linked network. Such chemistry is utilised in silicone sealants, with atmospheric moisture diffusing into the polymer once the sealant is extruded, hydrolysing the reactive groups on the cross linker. Fast curing speeds and the ability to modify the properties of the final polymer by using functional alkoxy silanes, deems this class of material an appropriate medium for the fabrication of optical waveguides.

A material suitable for applications in the fabrication of optical waveguides by TPA on PCBs has to withstand high temperatures, be compatible with existing PCB materials and processes, as well as form thin films with good adhesion. The developed material needs to contain high refractive index functional groups attached to the polymer backbone, as well as being compatible with a specific two photon photoinitiator. In order to produce optical waveguides by means of TPA, the absorption of the material at the wavelength of the laser has to be low, so waveguide structures can be fabricated below the surface layer. The photon density within the focal volume is high enough to initiate organic cross linking of acrylate functional groups. A silanol terminated dimethyl diphenyl siloxane was chosen, due to its optical properties and speed of curing at room temperature with acryloxymethyl trimethoxy silane. Using this tri functional cross linker it was possible to produce an optically transparent, flexible material, which contained high refractive index functional groups attached to the polymer back bone. In the presence of a tin catalyst, the material is fully cross linked in under an hour at room temperature. The acrylate functional groups, in the presence of a two photon photoinitiator are polymerised by two photon excitation using an ultra fast Ti-sapphire laser system. The inscribed waveguides were viewed by phase contrast microscopy and cut back investigations. The siloxane matrix material was then used in the study of the preparation of demonstrators, whereby opto-electronic components, mounted on modified substrates were connected by the inscription of 3D waveguide bundles. On-line measurements were carried out on the connected components during the inscription of the waveguides, which enabled the photocurrent to be detected.

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2. Experimental conditions

2.1 Materials

Silanol terminated dimethyl diphenyl polysiloxane (wt. % OH 0.7-1.3, mole % diphenylsiloxane 2.5-3.5), acryloxymethyl trimethoxy silane and dioctyl tin dilaurylate were purchased from ABCR GmbH (Germany), and used without further treatment. Irgacure 379 was supplied by CIBA Specialities (Basel, Switzerland).The specific two-photon photoinitiator 1,5-bis(4-(dimethylamino)phenyl penta-1,4-diyn-3-one (N-DPD) was utilised for all TPA experiments and was developed and synthesised externally [27]. This photoinitiator is extremely effective due to its conjugated π-electron system amplified by the dimethylamine groups resulting in the absorption maximum at a wavelength suitable for two-photon applications.

2.2 Preparation of optical material

In all experiments material compositions were based on silanol terminated polysiloxane cross linked with 20 wt. % acryloxymethyl trimethoxy silane. In order to obtain homogeneous and dust free layers, the components were mixed thoroughly and filtered using a 0.45 µm PTFE syringe filter. 0.025 wt. % N-DPD was dissolved in the cross linker, and the polymer and cross linker were stirred for one hour during which a pre curing occurs, increasing the viscosity of the material and making the application of the material onto substrates easier to produce thin layers. Following the sample preparation, thin films were prepared by scraping the material onto substrates to give film thicknesses of between 300 and 500 µm. The chemical structure of the silane components and possible cross linking mechanisms occurring during the curing steps are presented in Fig. 1. The material was then applied to substrates and cured at room temperature for one hour.

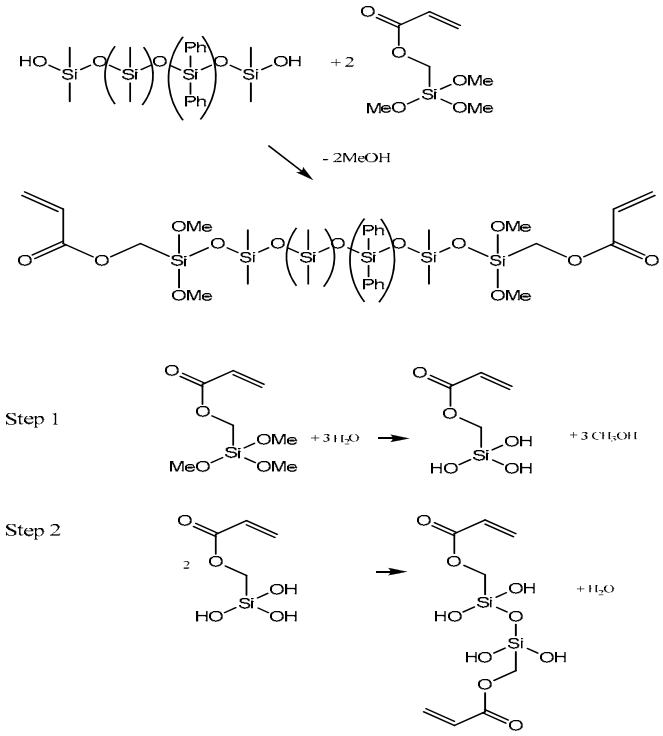

Fig. 1. Structure of acryloxymethyl trimethoxy silane, silanol terminated dimethyl diphenyl polysiloxane and possible cross linking reactions of polymer and cross linker.

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2.3 TPA structuring of optical waveguides

To structure optical waveguides, an ultra-fast Ti-sapphire laser system (Mai Tai, pulse duration 120 fs, repetition rate: 1 kHz) was utilised, at a wavelength of 800 nm. The laser can penetrate deep into the material, as linear absorption is not observed. A high intensity is required at the laser focus for multi-photon absorption to be achieved. Due to the non-linear TPA process, the interaction is confined to the laser focus, making it possible to fabricate three-dimensional structures inside the optical material. The laser is astigmatically focused by a 1:3 cylindrical telescope and a 20x microscope objective. The cylindrical telescope reduces the laser beam diameter in one dimension, and allows additional and symmetric shaping of the waveguide's cross-section.

To perform TPA material testing, the laser power was varied to determine the exposure conditions. Laser powers between 160 and 260 μW (0.8- 1.3 mW/cm^2) were used. Three dimensional optical waveguides were inscribed into the thin layers by means of two-photon induced polymerisation of the acrylate groups attached to the backbone of the polymer. The polymerisation of the acrylate functionality leads to an increase in the refractive index in the illuminated areas. Substrates used in this study consisted of either 76 x 26 mm microscope slides, which were used to examine the structured waveguides by phase contrast microscopy, or rigid-breakable FR-4 substrates, which are fibreglass reinforced epoxy resins used for the production of printed circuit boards (PCBs). The phase contrast images of the waveguide structures were studied using an Olympus BX 51 optical microscope and images were captured using a Colour View IIIu digital camera. The cross sections and depths of the waveguide structures were measured using Analysis® Five software. Specially designed FR-4 PCBs were used to produce demonstrators. The demonstrators were 10 cm x 5 cm, and consisted of a rigid base or a flexible polyimide foil. The components on the boards consisted of a VCSEL (vertical-cavity surface-emitting laser) which was mounted upright and emitted light at 850 nm parallel to the substrate surface, and a photodiode. In order to structure waveguides, the optical components were fully embedded in the optical material. Photocurrents of the demonstrators were recorded before and directly after TPA structuring using a Keithley 6485 Picoammmeter, with the laser diode driven with 6 mA by a Newport 505B Laser Diode Driver. The "photofactor" is defined as the ratio Φ_s/Φ_0 where Φ_0 is the photocurrent prior to structuring and Φ_s is the photocurrent recorded following TPA structuring.

2.4. Characterisation of material

For single-photon irradiation experiments an Omnicure s1000 spot cure lamp was used, with a standard 320-500 nm filter. Illuminations were carried out under nitrogen atmosphere, with the light guide 7 cm above the thin films of the optical material. The lamp used had an output of 18 W / cm^2.

Time-based FT-IR spectra were recorded with an FT-IR spectrometer (Spectrum One, Perkin Elmer). Samples were spin coated onto gold coated silica plates to obtain thin films. Samples were placed inside a wide angle reflection cell, which was purged with nitrogen.

Near infrared spectroscopy was carried out on an NIR spectrophotometer with integrating sphere. (PerkinElmer Lambda 950). The silanol material was cured in optical cuvettes, which were broken open to produce free standing samples. One sample was irradiated using an Omnicure spot cure lamp to induce polymerisation of the acrylate functional groups. The samples then represented the core and cladding material surrounding the waveguide.

Simultaneous thermal analysis (STA), coupled with mass spectrometry (MS), was carried out on an STA 449C Jupiter, and QMS 403C Aeolus, both from NETZSCH. Samples were heated at 10 K per minute, up to 300 °C.

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3 Results and discussion

3.1 Material properties

To determine the suitability of the matrix material for TPA applications, one photon experiments were performed to establish how efficiently the acrylate functional groups attached to the polymer backbone polymerise. Samples of silanol terminated dimethyl diphenyl polysiloxane, cross linked with acryloxymethyl trimethoxy silane, containing 1 wt. % dioctyl tin dilaurylate and 1 wt. % Irgacure 379 as photoinitiator were illuminated using a UV spot cure lamp (1.4 W / cm^2) and the double bond conversion of the acrylate functional group was monitored using time-based FT-IR spectroscopy. The UV exposure dose was taken from the UV lamp and was the dose delivered to the sample being cured. It was possible, using time based software, to record spectra of the thin films every 20 seconds whilst the sample was being continuously illuminated by a spot cure lamp. To examine the acrylate conversion under UV conditions using the photoinitiator N-DPD, samples were also prepared containing 0.025 wt. % of this photoinitiator, as well as a blank sample containing no photoinitiator. The conventional photoinitiator Irgacure 379 was also investigated; as this photoinitiator is commonly employed for single-photon initiated polymerisation, but has been found to also be effective in two photon applications [28]. N-DPD is extremely photo stable under single-photon conditions; however, it was important to determine the stability of the acrylate monomers in the cladding material. If the acrylate functional groups present in the cladding material polymerise on exposure to UV light, the difference in refractive index will decrease, leading to a breakdown of the wave guiding capabilities. The samples were exposed to UV light for 12 minutes, and the double bond conversion was calculated by using a reference peak in the corresponding FT-IR spectra, shown in Fig. 2. The conversion achieved using the conventional photoinitiator Irgacure 379 was almost 50% in the first 20 seconds, in comparison to N-DPD, with the conversion of less than 5% after the same time period. A conversion of 80% was reached after 3 minutes in the sample containing Irgacure 379, in comparison to a conversion of less than 10% for the sample containing N-DPD. A second study using a higher light intensity of 0.7 W/cm^2 resulted in the conversion of over 80% after 200 seconds using Irgacure 379, and 48% using N-DPD. The blank sample also showed a conversion of 28% after 200 seconds, which is to be expected as acrylates are highly reactive. A comparison of the double bond conversion using the different photoinitiators and light intensities is shown in Fig. 3. It can be seen that Irgacure 379 is a highly efficient photoinitiator, suitable for the initiation in the photopolymerisation of acrylates; however N-DPD is more suitable in this system, as post polymerisation in the cladding material needs to be avoided.

Near infrared spectroscopy was performed on illuminated and non illuminated samples of the silanol terminated polysiloxane cross linked with acryloxymethyl trimethoxy silane. The spectra are shown in Fig. 4. The main areas of interest were absorptions in the wavelengths 1310, 1550 and 840 nm, which are typical wavelengths for datacom and telecommunications. The spectra of the illuminated and non-illuminated samples revealed no major optical losses because the OH groups, which are known to be highly absorptive in the 1550 nm region, as well as aliphatic C-H groups [29], are only present on the terminal polymer chains, and the methyl groups on the polymer chain were partly substituted with phenyl groups. The optical losses in dB were calculated for the UV illuminated and non illuminated samples (Table 1).

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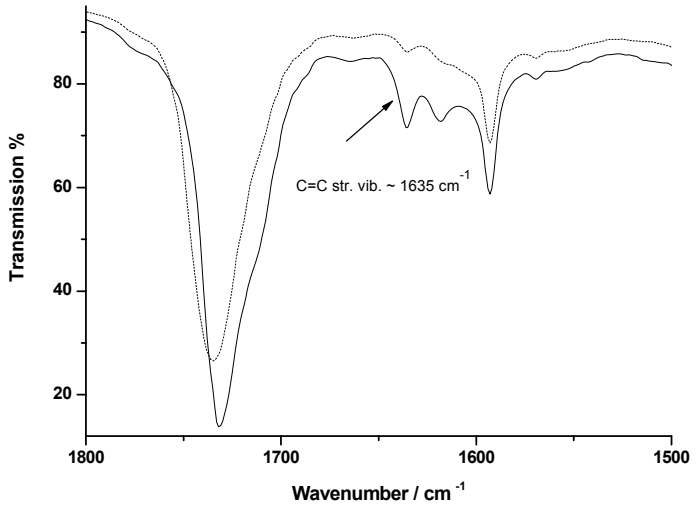

Fig. 2. Section of FT-IR spectra of silanol terminated polysiloxane cross linked with 20 wt. % acryloxymethyl trimethoxy silane before, (solid line) and after UV exposure, (dashed line).

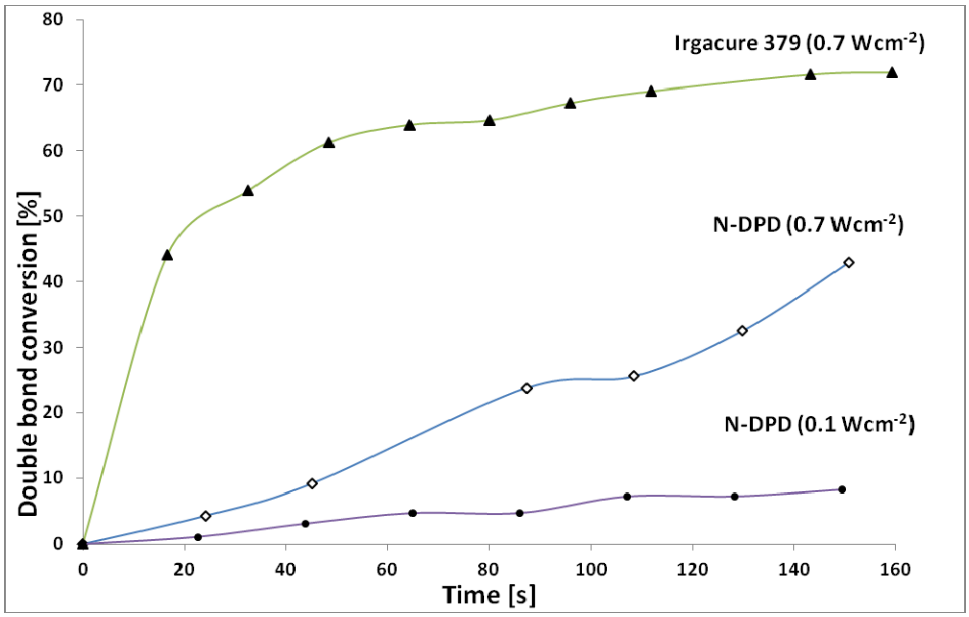

Fig. 3. % double bond conversion (DBC), (calculated from stretching vibration mode at 1636 cm^{-1}) of acrylate functional group during UV exposure of samples containing different photoinitiators and different light intensities. ▲ = Irgacure 379, UV intensity = 0.7 W/cm^2 ● = N-DPD, UV intensity 0.1 W/cm^2, ◊ = N-DPD, UV intensity 0.7 W/cm^2.

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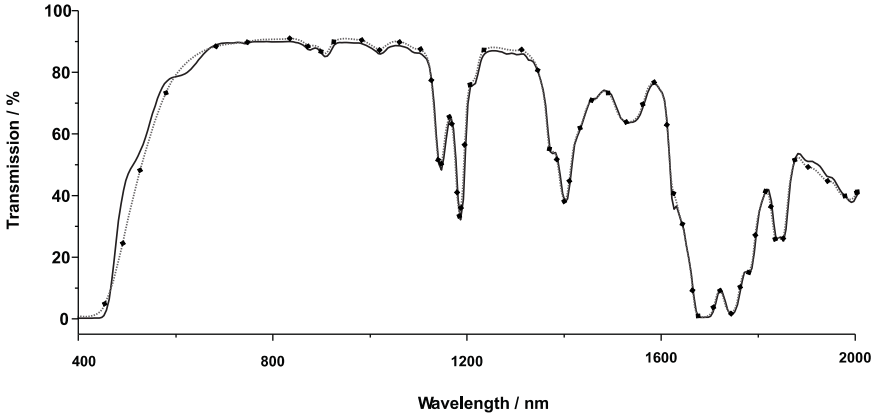

Fig. 4. NIR spectra of non-illuminated (dashed line with dots) representing the cladding material, and illuminated (solid line) representing the waveguide core material of silanol terminated polysiloxane cross linked with acryloxymethyl trimethoxy silane.

Table 1. Calculated optical losses in dB/cm for illuminated and non-illuminated material at selected wavelengths

	dB/cm (non illuminated sample	dB/cm (illuminated sample
Wavelength [nm]		
840	*0.41*	*0.46*
1310	*0.59*	*0.65*
1550	*1.85*	*1.87*

A material suitable for optical applications on printed circuit boards has to be stable enough to be able to withstand harsh PCB processing steps, including temperatures >220 ° C. The thermal stability of the silanol terminated polymer cross linked with 20 wt-% acryloxymethyl trimethoxy silane was evaluated by simultaneous thermal analysis coupled with mass spectrometry. The samples were heated from 30 −300 ° C at a heating rate of 10 K per minute. The samples which were cured at room temperature, and received no further treatment, showed a weight loss of 5% at 200 ° C, compared to a sample, prepared in the same way, but thermally treated firstly for one hour at 150 ° C followed by 200 ° C for ten minutes. From the MS data it was clear that the condensation products water and methanol were responsible for the weight loss. The condensation products can be removed from the matrix material during the thermal treatment, as shown by the absence of these peaks in the spectra corresponding to the thermally treated samples. A thermal stability of over 200 ° C is therefore obtained when a thermal process is carried out to fully stabilise the material. Decomposition of the material did not occur until above 250 ° C, clearly showing that after the removal of any condensation products, the material is well suited for PCB applications.

3.2 Fabrication of optical waveguides

Films of the optical material with a thickness of 200 - 300 μm were prepared on optical glass and FR-4 rigid-breakable substrates. Linear waveguides were inscribed by means of selective TPA of the acrylate functional group attached to the polysiloxane backbone. 0.025 wt. % N-

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DPD was used as photoinitiator. The structuring of the optical waveguides was carried out using an ultra fast Ti-sapphire laser system at a wavelength of 800 nm, (Mai Tai, pulse duration: 120 fs, repetition rate: 1 kHz). To test the suitability of the material for TPA, laser powers were varied in order to determine the different exposure conditions and the behaviour of the optical material. Laser powers between 160 and 260 µW (0.8-1.3 mW/cm^2) were used to inscribe the waveguide structures. Waveguides with a length of 5 mm were inscribed into the matrix material, with a control through feed rate of 20 mm min^{-1} relative to the laser focus. This translation velocity was chosen as it was found to be the optimum speed to perform structuring, leading to high contrast waveguides and no burning of the polymer matrix. The depth of the waveguides in the material was between 100 and 200 µm. The waveguide structures were observed by phase contrast microscopy and are shown in Fig. 5. With an increase in laser power, the lines gradually increased in contrast. Laser powers of over 260 µW led to some burning of the waveguide structures. In order to observe the shape and size of the waveguide cross sections, short sections of waveguides were inscribed on rigid-breakable FR-4 substrates, which enabled the waveguides to be cut. Short sections of waveguides were inscribed over breakable parts on the substrates, were then cut to obtain a clean surface. The waveguide cross sections were characterised by optical microscopy. The cross sections are shown in Fig. 6. Damage to the polymeric material occurred during cutting through the matrix to observe the cross sections. Waveguides with diameters of up to 45 µm were achieved with laser powers of 250 µW.

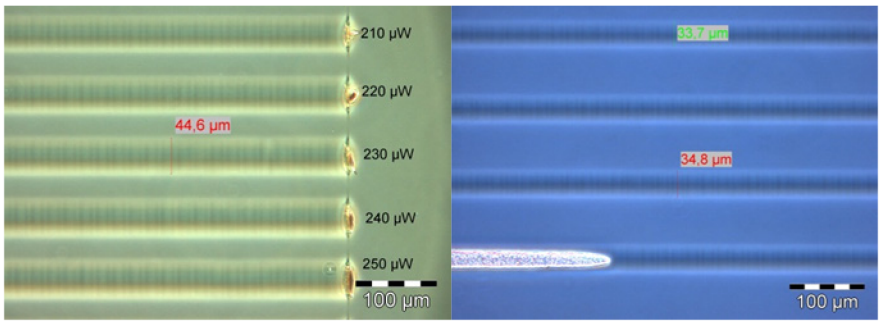

Fig. 5. Waveguide structures inscribed using different laser powers 190-230) detected by phase contrast microscopy.

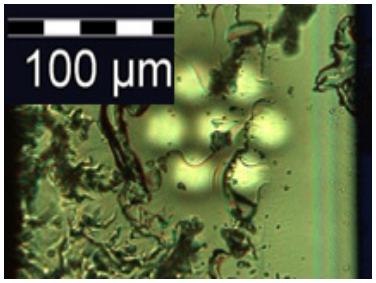

Fig. 6. Waveguide bundle cross section observed by optical microscopy, structured with a laser power of 200 (1mW/cm^2) – The irregularities observed in the image arose from the method of cutting the flexible matrix material to view the cross sections.

In addition to phase contrast microscopy, propagation loss measurements were performed by using the cut-back method. Waveguides were cut at different lengths and the intensity of the transmitted light was measured. After obtaining a clean cross section of the material and observing the waveguides, light was coupled by butt-coupling. Both ends of the waveguide were cut to enable in- and out-coupling. The laser light used had a wavelength of λ = 633 nm, and the output was recorded using a CCD camera. The laser powers used to structure the

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waveguides affected not only the size of the cross sections of the waveguides, but also the optical losses. Cut back measurements performed on a number of different waveguides revealed that higher laser powers resulted in waveguides with low optical losses, with two waveguides structured with a laser power of 210 μW having propagation losses of 0.43 dB/cm and 0.22 dB/cm. The measured losses are attributed to volume and surface scattering as well as absorption. Any imperfections or contaminants present in the matrix material lead to scattering centres. Any rough or irregular surfaces of the waveguide interfaces, which are seen to improve with higher laser powers as observed using phase contrast microscopy can cause diffuse reflection. The matrix material itself also contains functional groups such as a small percentage of hydroxyl groups which have a strong absorption in the IR region affecting the optical transmission at 1300 and 1550 nm which lead to significant optical losses.

3.3 Development of optoelectronic PCBs

Two-photon Photopolymerisation was used to fabricate waveguides to produce optoelectronic PCBs. The optical material was applied to specially designed PCB substrates with mounted components. The material was cast evenly to produce a smooth layer and achieve full covering of the mounted optoelectronic components. The optoelectronic components are directly mounted on the substrate completely covered in the optical material. The optoelectronic PCB is shown schematically in Fig. 7 . The layer thickness of the material on the PCB was between 200 and 300 μm. The waveguides are directly structured with high precision using TPA, between the photo and laser diodes. Each board contained an 850 nm vertical-cavity surface-emitting laser, which was mounted upright to allow the emitting area to point towards the laser diode. An exact 3D analysis of the sample surface is required prior to the TPA fabrication. This allows the alignment of the waveguide relative to the active area of the optoelectronic components. The lateral alignment of the components was determined by using a CCD camera located next to the microscope objective, which enables the x-y positions of the laser and photodiodes to be determined and to define the depth at which the waveguide is structured. The surface of the optical material along which the waveguide is inscribed, is set by monitoring the intensity of the back-reflected light of a He-Ne laser with a photodiode in a confocal setup. The second method is also used to define the z position of the optical components, allowing the start and end point of the waveguide within the optical material to be defined. Correct alignment allows for efficient coupling of light in and out of the waveguides. Once the x, y and z coordinates of all components have been defined the laser focus is scanned across the layer of the acryloxy functional polymer, which forms an optical waveguide between the laser and photodiodes. A bundle of waveguides were inscribed between the diodes, consisting of a centre waveguide surrounded by six waveguides). The bundles produced had cross sections of up to 90 μm, shown in Fig. 8. During the structuring of the waveguides, the laser diode is fully functional, enabling the continuous increase of the photocurrent. The photocurrents after TPA structuring and after storage are presented in Fig. 9 and showed an average photofactor (Φ_s/Φ_0) of over 7000. The demonstrators were all stored in dark conditions for two to four days, and the photocurrent measurements were repeated. Results of the photocurrent measurements are shown in Fig. 9. It is likely the interconnecting network of the polymerised acrylate functionality in the waveguide core improves during storage. The photocurrent continued to increase for one week, during which the photocurrent was monitored regularly. All PCBs with correctly working diodes and good layer properties of the optical material showed an increase in the photocurrent following the TPA structuring, with stable photocurrents being recorded for over two years.

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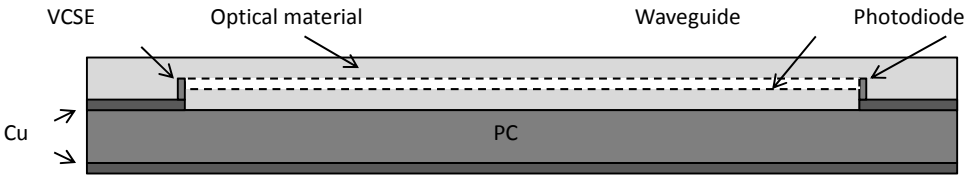

Fig. 7. Schematic representation of an optoelectronic PCB.

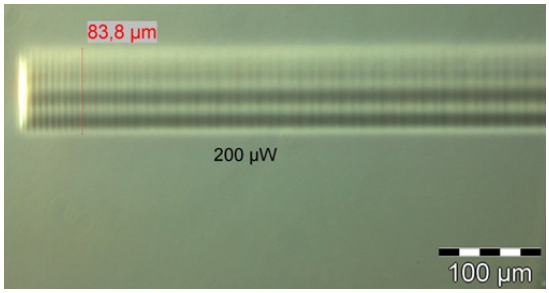

Fig. 8. Bundle of 7 waveguides structured with a laser power of 200 µW detected by phase contrast microscopy.

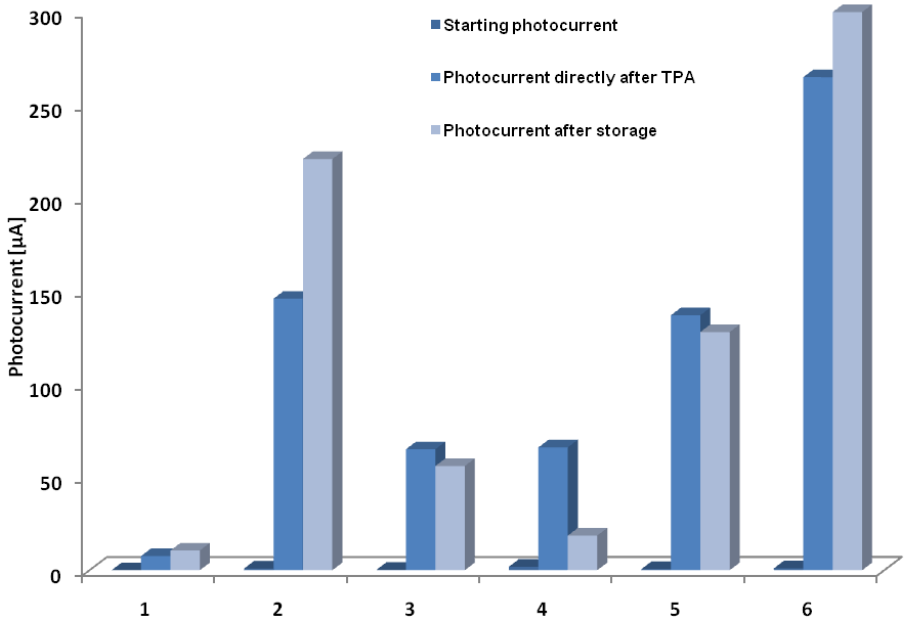

Fig. 9. Photocurrent measurements of PCB demonstrators directly after and a few days storage TPA structuring.

4. Conclusion

Using a silanol terminated polysiloxane and acryloxy functional silane as cross linker, we have developed and characterised an optical material, utilised for applications in the fabrication of three dimensional waveguides by two-photon induced polymerisation. The matrix material is stable enough to withstand processing requirements, is easily produced and is suitable for uses in 3D microfabrication of optical waveguides. When used in conjunction with the specific two photon photoinitiator N-DPD, waveguide structures with cross sections of up to 50 µm were achieved. The waveguides produced were characterised by light

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extraction tests which confirmed the light guiding of the written structures and optical losses of the waveguides measured using cut-back techniques were confirmed to be between 0.6 and 0.3 dB/cm at a wavelength of 850 nm. Waveguide bundles were successfully fabricated on specially designed PCB substrates to produce optical interconnects. The increasing photocurrent of the optical components was monitored during structuring, with stable photocurrents being recorded for over two years.

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