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CO_2 laser micromachining of optical waveguides for interconnection on circuit boards

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ABSTRACT

The introduction of microvia and surface mount technologies into the manufacturing process for printed circuit boards (PCBs) has significantly improved the interconnection density. However, as the speed of signals for data communication on the board approaches and begins to exceed 10 Gb/s, the loss and crosstalk of copper interconnections increase. To resolve these problems, optical interconnections (OI) have been suggested as a viable solution. Literature reports have proved the photochemical nature of excimer laser ablation with its minimal thermal effect, and other ultra-violet lasers are also being investigated for the fabrication of polymer waveguides by laser ablation. In this paper, the authors demonstrate the fabrication of multimode optical polymer waveguides by using infra-red 10.6 μm CO_2 laser micromachining to etch acrylate-based photopolymer (Truemode^{TM}). CO_2 lasers offer a low cost and high speed fabrication route as CO_2 lasers can be used to cut through various engineering materials including polymers and metals. The paper characterises the relationship between the laser ablation power, the fabrication speed and the resulting effect on the waveguide optical insertion loss for the first time.

1. Introduction

The integration of optical waveguide interconnects into and onto printed circuit boards (PCBs) is of increasing interest with the demand for higher data transmission rates between components and between separate boards in a system. A number of approaches to this have been presented in the literature, but the use of optical polymer materials to create multimode waveguides is one of the most attractive as the materials and processes are largely compatible with existing PCB manufacturing processes. In this scheme the core of the waveguide and cladding are prepared from polymers with different refractive indices that enable total internal reflection to take place, confining the optical signal within the core. Alternative polymer materials have been proposed including silicones [1,2], ORMOCER [3], epoxy resin [4] and acrylate [5] that are typically supplied in a liquid state and may be cured using UV radiation such that they may be patterned using photolithography, laser direct imaging, inkjet printing and laser ablation [6], the latter of which is the subject of this paper.

Being among the first generation of commercial lasers [7,8], the CO_2 laser is one of the most widely used gas lasers operating mostly in the CW (continuous wave) mode, albeit pulsed mode operations are now being used. They are highly efficient with relatively low maintenance cost and high processing speed [7,8]. The power output from CO_2 lasers varies from as low as 10 W to a very high power of tens of kilowatts used in industrial applications e.g., welding, soldering, drilling, cutting and heat treatment [7–10]. The wavelength of CO_2 lasers is in the mid-IR region characterised by heat generation, making the laser a good source of heat required in thermal or thermal-related applications where heat generation is not an issue of concern, rather a merit [11–13]. Unlike mechanical drilling, CO_2 laser machining is a non-contact process which depends significantly on the thermal, optical and/or chemical properties of the materials to be processed [10].

Reports [14–16] are now available on the use of a CO_2 laser for optical waveguide fabrication based on changing the refractive-index of the materials. In these investigations, the refractive index of the region adjacent to the ablated site was reduced by an order that was typical of the difference in cladding-core refractive indices required for the containment of light by total internal reflection (TIR). This process was thermal and the region of the reduced index was the area affected by the heat diffused from the irradiated site, which was not sufficient enough to cause any etching; that is to say, it was the heat affected zone (HAZ) which

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represented the cladding in this scheme. The modification of refractive index in this case appears to be due to the thermal characteristic of the CO_2 laser -material interaction, but is material dependent as recently reported in [17], where benzocyclobutene (BCB) showed refractive index changes at beam energy densities of 100 mJ/ mm^2 to 180 mJ/ mm^2, while epoxy OPTOCAST 3505 had zero refractive index change for the same range; in other words, laser irradiation at the CO_2 laser wavelength (i.e., 10.6 μm) does not necessarily mean a change of refractive index.

In addition to refractive index modification, there are various approaches being adopted for the fabrication of polymer waveguides using lasers [18–20]. In this case, the scheme of Fig. 1 is followed, where layers of cladding and core material are first deposited, and then the laser is used to remove the deposited polymer material, leaving behind ridges of the core polymer. These are then covered with more cladding material to confine the light within the core structure. Laser ablation of polymer waveguides is often based on material removal using mainly excimer [3,20–22] and, to a certain degree, UV Nd:YAG [18,20]. In the area of optical waveguide fabrication, little work other than the refractive index modification mentioned above has been carried out using CO_2 lasers for the purpose of polymer waveguide fabrication. The authors of [23] reported patterning multimode ‘lightguides’ in PMMA using a pulsed CO_2 laser for micromachining, but information such as the optical loss and polymer deposition technique were not provided. A CO_2 laser has also been investigated for fast cutting of structures followed by UV laser machining for fine slow machining [Geert van Steenberge (TFCG Microsystems, IMEC Ghent University)—private communication]. This concept is similar to that of Williams et al. [24], where an excimer laser was employed to smooth ablated tracks in ceramic that were first formed using a TEM_{00} pulsed CO_2 laser. Typically, the chemical bond energies of optical polymers are usually in the range of 3–8 eV [25]; this is more than an order of magnitude compared to the photon energy of a CO_2 laser operating at 10.6 μm wavelength, which is only 1.88×10^{-20} J (or ~0.1 eV). As such, machining with a CO_2 laser usually occurs by thermal interaction between the laser beam and the material, contrary to the bond-breaking of the polymer molecules often associated with short wavelength lasers.

The CO_2 laser and Nd:YAG are often used in the processing of PCB materials where machining is performed to create vias between layers of the circuit board [10,13,26]. This is another reason why the application of CO_2 laser micromachining of the photopolymer is attractive as its successful implementation will lead to better compatibility with the existing PCB manufacturing process and infrastructure. In this paper, the results of an investigation of the CO_2 laser micromachining of Truemode^{TM} photopolymer to create optical waveguide structures are presented. The effect of laser operating parameters on the ablation of the photopolymer was studied to determine the depth of ablation and optical waveguides were fabricated and characterised to demonstrate the feasibility of the technique.

2. Research methodology

2.1. Laser system

The CO_2 laser used in this study was a commercially available air-cooled SYNRAD series-48 IR laser source with a fundamental wavelength of 10.6 μm and maximum power of 10 W. The laser operated in the CW mode with a Gaussian TEM_{00} beam profile with a spot size specified as 250 μm at 1/e^2. It used WinMark Pro® software to control the experimental parameters such as power and speed of laser scanning, with the maximum scanning speed achievable of 3000 mm/s. In all cases, the sample remained stationary while the beam was scanned across the surface using a mirror system within the delivery optics to control its position.

2.2. Optical polymer material

Truemode^{TM} polymer (provided by Exxelis Ltd, Edinburgh, UK) was used in this research. It is a UV-curable mixture of acrylate and methacrylate monomers with initiators and accelerators that is liquid at room temperature. The fact that its absorption loss is very low with a typical value of < 0.04 dB/cm @ 850 nm wavelength [27] in photolithographically fabricated waveguides and that it can withstand conventional PCB fabrication, i.e., high pressure lamination and high temperature solder reflow processes, makes it a suitable choice for OI [19,27]. The polymer formulations used for this study, as there are various types available from the manufacturer, were EXX-clad 277 (cladding material) and EXX-core 37E (core material) having refractive

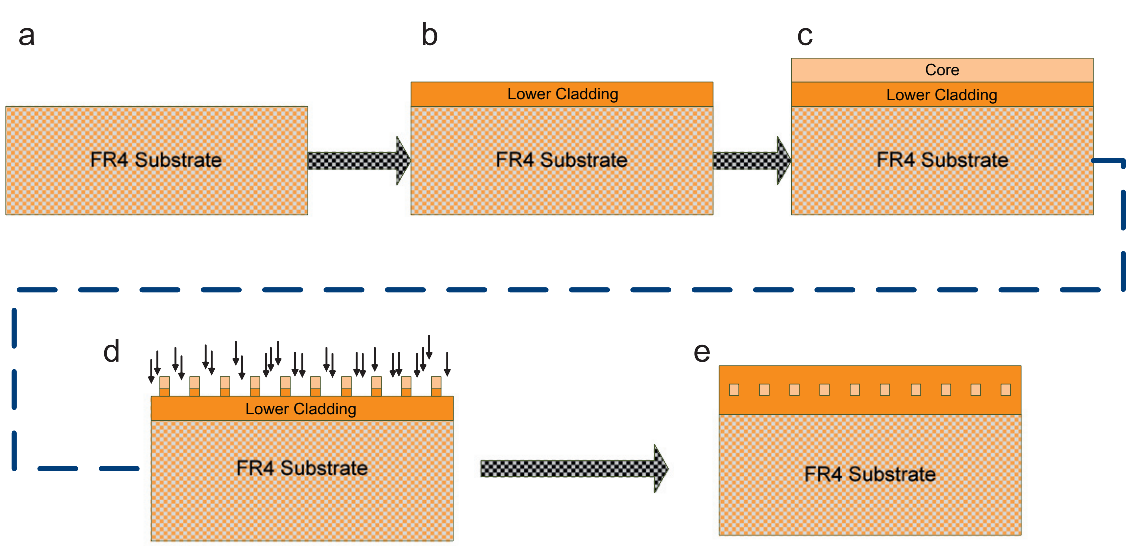

Fig. 1. Schematic diagram (side view) of the three major stages in the fabrication of optical waveguides by laser ablation: (a) A bare substrate of FR4 that has been cleaned, (b) spin coating of lower cladding followed by UV curing, (c) spin coating of core followed by UV curing, (d) laser ablation of the optical layer from the core through to the cladding layer, and (e) Deposition of the upper cladding.

indices of 1.5265 and 1.5560, respectively at 850 nm. This wavelength, 850 nm, corresponds to the wavelength at which optical loss measurement was carried out for the fabricated waveguides as discussed later.

2.3. Fabrication process

The stages involved in laser ablation of a single layer polymer waveguide as employed in this research are shown in Fig. 1, which is similar to that previously reported [18]. Details of the sample preparation process can be found in [18], but briefly, consisted of cleaning and drying the FR4 substrates before the layers of Truemode™ optical polymer were deposited by spin coating at about 350 rpm for 30 s to obtain 30–50 μm thickness for the core layer, typical of that required for a multimode waveguide [28–30]. The lower cladding and core layers were deposited sequentially, with the lower cladding layer cured before deposition of the core layer. Curing of the polymers was carried out by exposure to UV light for 3–4 min in a nitrogen atmosphere to cross-link the polymer (while stopping the inhibition due to oxygen) and finally oven-baked at 100 °C for 60 min.

3. CO_2 laser micromachining of optical polymer

Owing to the limited literature on the use of this class of laser for polymer waveguide fabrication by laser ablation rather than material modification as earlier pointed out, an initial study was carried out to determine the feasibility of machining the chosen optical polymer in order to characterise the process. For this, samples of core material deposited on cladding were used (i.e., FR4-lower cladding-core) and straight lines were machined using laser powers varying from 1 to 9 W and a scanning speed range of 20–500 mm/s. While ablating at high powers and low speeds, a charring-like effect (with smoke emanating occasionally) at the ablation zones was observed—an indication of a thermal process, however with lower power and faster speed, tracks could be machined in the polymer.

The IR laser ablation process is predominantly [9,10] thermal, it thus follows that for example, a scanning speed of 100 mm/s at 1 W of energy would likely produce the same effect as that carried out at 200 mm/s and 2 W when machining on this system. It is on this premise that the authors consider that the laser ablation using this CW CO_2 laser could be modelled by calculating a 'scanning energy density (SED)', obtained by dividing power with speed, measured in J/mm. Therefore, it is possible to plot the relationship between the widths of ablated channels and the parameters used, represented as SED, as shown in Fig. 2a. From this, it is evident that the track width increases with an increase in the scanning energy density; however the rate of increase gradually reduces as the values of SED become higher. This is because as the energy density is increased, so is the absolute beam intensity across the profile, which means that more power would be available at the ablation zone, especially at the region close to the edge of the Gaussian profile where no ablation would have occurred if low energy density were to be used. This is schematically shown in Fig. 3. Thus, the ablated channel will have a depth and shape that is a function of the position of the threshold line, which is in turn a function of both the beam power and scanning speed, i.e., energy density. A plot of depth of ablation against SED (Fig. 2b indicates a direct relationship between the two quantities). Fig. 2a also identifies the laser power level used to achieve each particular data point, it is clear that within the range of powers under investigation that using SED to characterise the energy input to the sample is a reasonable approach, as for example, samples machined with 2 W (50 mm/s)

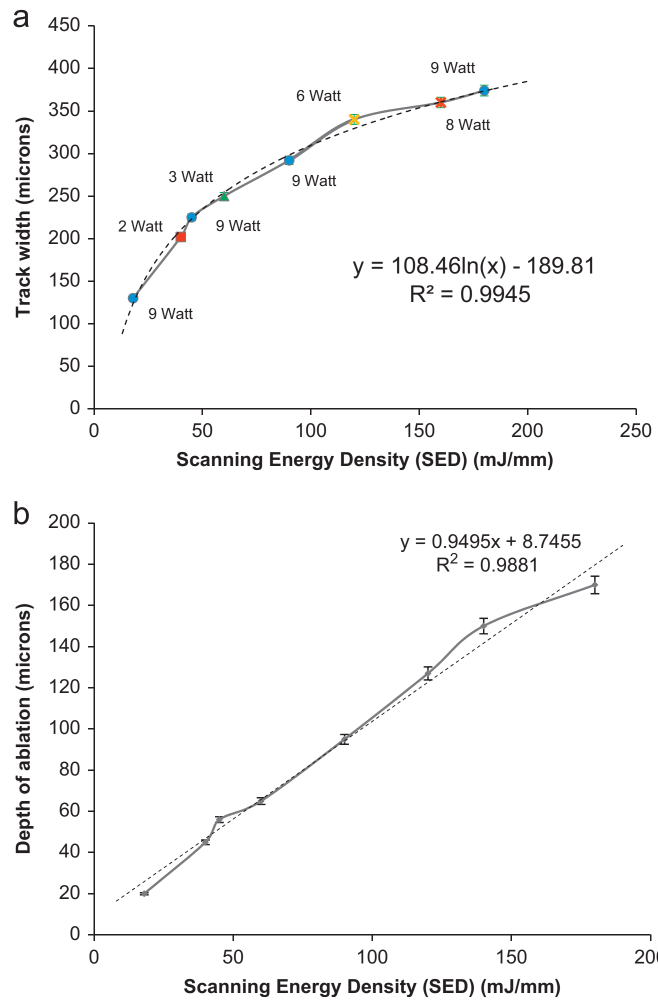

Fig. 2. Graphs for micromachining carried out on Truemode™ optical polymer showing the relationship between: (a) the scanning energy density (SED) and the resulting ablated track width, and (b) the scanning energy density and the depth of ablation.

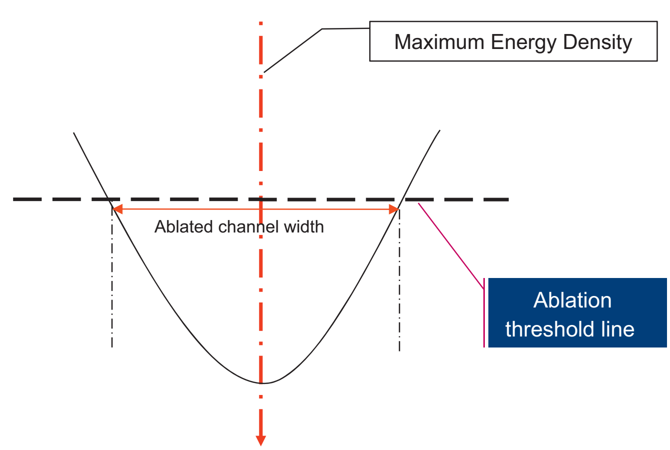

Fig. 3. Schematic diagram of the CO_2 laser beam profile showing how the power intensity and energy density threshold affect the width of ablated channels.

and 9 W (200 mm/s) with similar SED gave similar track widths and ablation depths.

Following this study it was observed that maintaining the energy density (or SED) in the range of 30–50 mJ/mm produced suitable structures required for patterning of multimode waveguides as this would be sufficient to etch through ≥ 30 μm of core layer. It can therefore be argued that SED values, which combine the effects of the two changeable parameters used on the system, can be used as a guide for CW laser ablation of polymer waveguides at $\lambda = 10.6\ \mu m$.

4. CW CO_2 polymer waveguide fabrication

The fabrication of polymer waveguides was carried out as described in Fig. 1 using the preferred parameters obtained from the micromachining study. Fig. 4 is an example of four adjacent waveguides formed by micromachining parallel trenches in Truemode^{TM} polymer. The waveguides in this image were illuminated by passing light (from a Flash^{TM} 200 optical measuring device) into one end of the guide, which had been cut with a dicing saw, mounted using epoxy resin and polished, for possible detection at the other end, i.e., backlighting. The lines that can be seen in the image are thought to be scratches left by the polishing process which could be avoided in the future by further polishing, although this would not impede backlighting of the waveguides. It is clear that the shapes are trapezoidal, primarily due to the curved nature of the trenches, caused by the Gaussian nature of the beam and its circular shape. At this time, it is not known from the literature whether this shape will affect the propagation loss; laser ablated waveguides using either an excimer or UV Nd:YAG are often slightly tapered [18,20], but in their case, the tapering angle is significantly smaller. Furthermore, while the height of the four waveguides are identical (defined by the thickness of the core layer deposited), their widths appear to be different, which is thought to be caused by discrepancies in the spacing between the machined trenches.

Following the successful fabrication of waveguides at this wavelength, the authors considered investigating the effect of fabrication settings on the optical propagation loss. For this, a series of waveguides were made mainly to investigate the effect of machining power and speed in the range from 80 mm/s to 120 mm/s and powers between 3 W and 5 W; these corresponded to SED values between 30 mJ/mm and 50 mJ/mm. For this range of SED values, as shown in Fig. 2b, the expected depth of ablation was between $\sim 30\ \mu m$ and $\sim 60\ \mu m$ which guaranteed the machining of the core layer (and, in other cases, into the lower cladding layer) of the samples used. The propagation loss measurements of the waveguides were carried out at University College London (UCL) using an input spatially multimode (MM) uncooled vertical cavity surface emitting laser (VCSEL) at nominally 850 nm wavelength (depending on its temperature) as the input light source and launched via a 50 μm step index MM fibre, which is fully detailed in [18]. In each case, five waveguides in a group were fabricated at 50 mm long using the same laser ablation parameters. The waveguide samples were manually polished and index matching fluid ($n = 1.5433 \pm 0.0005$ at 840 nm) was applied at both the waveguide launch and exit facets. Optical insertion loss measurements were carried out for each of the five waveguides in a group machined with the same parameters and the mean values were taken of their losses. Fig. 5 is a plot of insertion loss against the variable parameters and the error bar is the standard deviation of the five measurements. With varying power (Fig. 5a) the insertion loss showed a minimum value at 4 W; on the other hand, with changing speed (Fig. 5b), the insertion loss showed only a small variation with a maximum at 80 mm/s. From these results and the fact that there is no linearity in relation between these quantities, it appears that the best operating parameters would have to be deduced by either choosing the setting which gives the minimum propagation loss and improve on this or by extending the range of parameter combinations. However, since the SED value also determines the ablated track width, it thus follows that this can also be a contributing factor to the loss variation. In this study, the least insertion loss of 10.7 ± 0.5 dB was achieved at 100 mm/s and 4 W. Using $y = ax + b$, where, y, x, a and b are the Insertion loss, Propagation loss, Waveguide length and combined input and output Coupling loss, respectively, the propagation loss was estimated to be 1.3 ± 0.5 dB/cm. This is quite encouraging considering the values reported for multimode waveguides using various fabrication methods [31] – < 0.02 dB/cm and 0.6 ± 0.03 dB/cm being the minimum and maximum propagation loss at 850 nm wavelength – and it is viewed as a means of facilitating the deployment of a multimode optical waveguide at a reasonably low manufacturing cost.

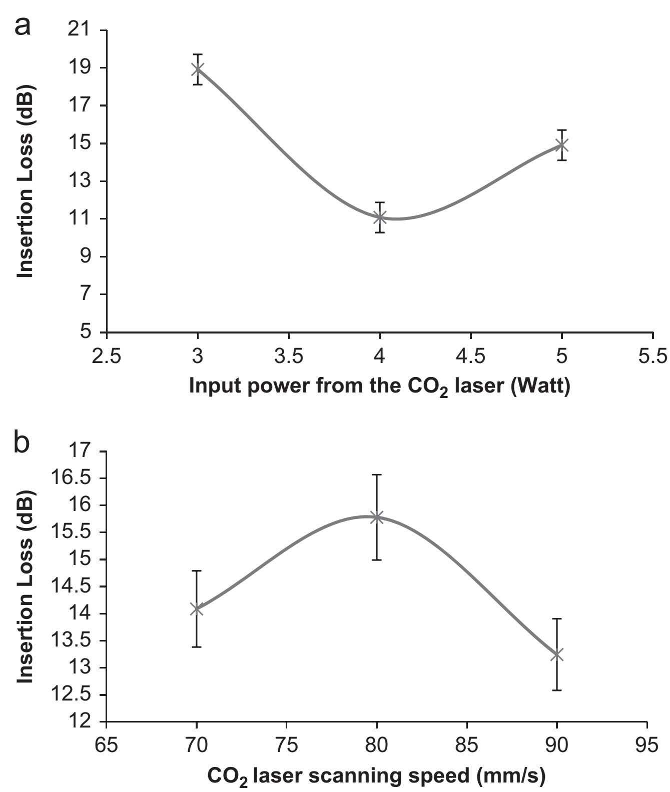

Fig. 5. Optical loss measurement carried out on optical waveguides showing (a) the insertion loss dependence on the laser ablation power at a constant scanning speed of 100 mm/s, and (b) the insertion loss dependence on the scanning speed at a constant laser ablation power of 3.5 W.

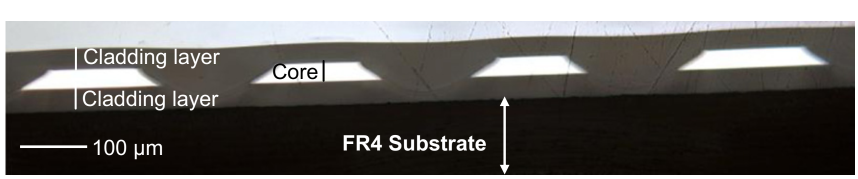

Fig. 4. Optical microscope images showing four adjacent waveguides machined using a CO_2 laser in Truemode^{TM} acrylate photopolymer at an input power of 4.0 W and speed of 100 mm/s.

5. Conclusion

IR CW CO_2 (at 10.6 μm wavelength) laser micromachining of optical polymer to form waveguide structures was considered in this paper. Laser ablation was chosen, among the potential candidate techniques, because of its current usage in the drilling of microvias in PCBs and equally because of its capability. The choice of 10.6 μm CO_2 lasers was primarily based on their processing and relative cost effectiveness when compared to an Excimer laser, thus facilitating the deployment of optical interconnection.

Combinations of laser power and scanning speed were investigated and it was found that scanning energy density (SED = laser power/scanning speed) provided a good representation of their combined effect on the machining process. Depth of ablation was found to be approximately linear with SED, and an SED value of 50 mJ/mm resulted in 60 μm depth of ablation, which was adequate to ablate through the core into the lower cladding of a typical multimode waveguide. Additionally, the ablated tracks were found to have varying widths with changes in SED that could be explained in terms of the intensity profile and ablation threshold.

Optical waveguides were fabricated, and the effect of input power and scanning speed, corresponding to SED values between 30 mJ/mm and 50 mJ/mm, on optical propagation loss were considered. Plots of the varied quantities against the insertion loss did not indicate a strong relationship between them; the least insertion loss of 10.7 ± 0.5 dB however was achieved at 100 mm/s and 4 W, which gave an estimated propagation loss of 1.3 ± 0.5 dB/cm. Although the insertion losses obtained here are relatively high nonetheless, the ability to successfully demonstrate that such a process can be accomplished with a CO_2 laser is key to a low-cost production route, since these lasers are currently used for high volume PCB production, while loss improvement should be considered in the future.

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