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Laser Ablation for Polymer Waveguide Fabrication

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1. Introduction

An increase in interconnection density, a reduction in packaging sizes and the quest for low-cost product development strategy are some of the key challenges facing micro-opto-electronics design and manufacture. The influence of high-density, small-sized products has placed significant constraints on conventional electrical connections prompting various fabrication methods, e.g. photolithography, being introduced to meet these challenges and ameliorate the rapidly changing demand from consumers. While high-power solid state lasers are fundamental to large scale industrial production, excimer laser on the other hand has revolutionised the manufacturing industry with high precision, easy 3D structuring and less stringent production requirements. Micro-structuring using excimer laser, best known as laser ablation, is a non-contact micro- and nano-machining based on the projection of high-energy pulsed UV masked beam on to a material of interest such that pattern(s) on the mask is transferred to the substrate, often at a demagnified dimension with high resolution and precision. The use of mask with desired patterns and beam delivery system makes the fabrication in this case accurate, precise and easily controllable. The first part of this chapter introduces the fundamentals of laser technology and material processing. In the second part, optical interconnects as a solution to 'bottlenecked' conventional copper interconnections is introduced with emphasis on excimer laser ablation of polymer waveguides and integrated mirrors. Key research findings in the area of optical circuit boards using other techniques are also briefly covered.

2. Introduction to laser technology

The word 'laser' has been part of the lexis of the English language since its invention in 1960 and subsequent commercialisation few years later. It is an acronym that stands for Light Amplification by Stimulated Emission of Radiation, which is considered a modified version of its predecessor - 'maser' (Microwave Amplification by Stimulated Emission of Radiation); in other words, laser is an optical maser. The first laser, ruby, emitted red-coloured light at $\lambda = 694.3$ nm. Just over five decades later, laser (and laser technology) controls a remarkable market share in various applications ranging from research and medicine, to manufacturing and domestic applications. One of the sectors that have seen dramatic advancement with the advent of lasers is medical surgery (e.g. ophthalmology, cosmetic surgery and dentistry).

Laser generation has been extensively covered in the literature, but essentially, but essentially there are three principles that must first take place: (i) stimulated emission to defeat spontaneous emission and absorption, (ii) population inversion to temporarily disturb normal distribution - these two processes require movement of species from a lower energy level to a higher one, and (iii) a feedback system to amplify the photon population.

2.1 Laser micromachining (or material processing)

Laser material processing is generally, though not technically, referred to as laser micromachining of engineering materials e.g. polymer, metals, glass and ceramics. This definition thus excludes applications of lasers to, for example, human tissues even though the mechanism is similar. The possible reason for this exclusive usage might be because early laser candidates found application in engineering sectors such as drilling and cutting of materials where high energies are needed. For laser micromachining, there are four key processes of importance (Figure 1).

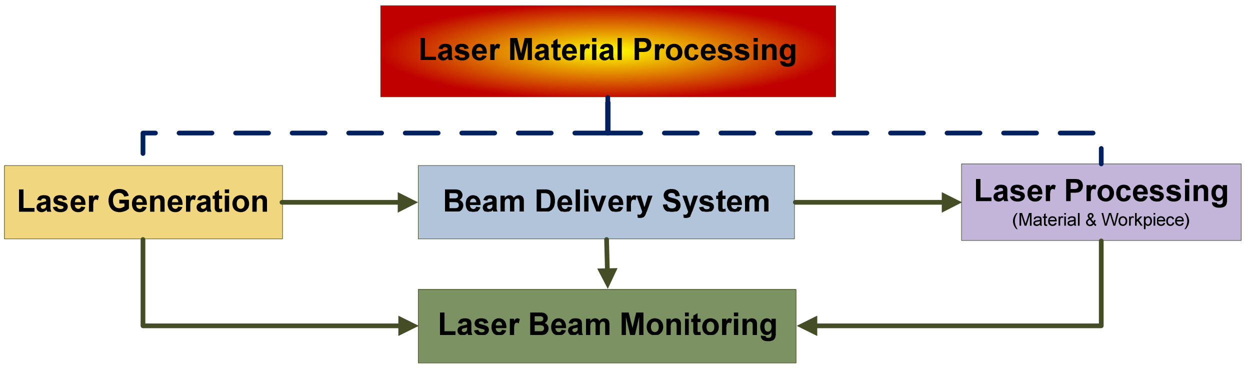

Fig. 1. Schematic diagram showing key stages of a typical laser material processing.

Beam generation

This is the first stage and the backbone of any material processing; its output determines the components of the remaining stages. For example, if a ceramic material is to be processed then the output at this stage should be a high-powered laser. Furthermore, if the ceramic is to be processed with minimum thermal damage then the output beam should, for example, be a pulsed laser with short pulse duration to provide a minimum time interaction between the beam and the material.

Beam delivery or propagation

This involves transporting the output beam to the site of processing or workpiece. What constitutes the beam delivery system depends on the application. In general, the elements of the stage, whose number and arrangement varies, include various optical devices such as mirrors, lenses and attenuator among others. It is therefore imperative that careful combination is made to achieve optimum result without losing much power as a small fraction of beam energy is lost per element. Also to be considered is the length of the path between the laser chamber output window and the workpiece. This needs to be kept to a minimum in order to avoid beam profile distortion and divergence. Excimer laser usually has the longest beam path with the highest number of optical components while a CO_2 laser employs the least.

Laser beam monitoring

Many of the laser beam properties are essential for an optimum process. However, three of these - energy, beam diameter and beam profile – are highly important in micromachining. There are two methods of obtaining the beam energy. In the first approach, the beam is sampled during the processing; this provides an accurate account of beam energy utilised during a particular process. It is pertinent to note that this task is in some way difficult and risky. Three methods of beam sampling: static beam splitter, rotating chopper mirror and leaky resonator mirror are discussed in [Crafer & Oakley, 1993]. The second approach is by total beam measurement; this approach involves measuring the energy at the workpiece using a power meter. Although the method might not totally account for what happens during a process, it is easier than the sampling method [Crafer and Oakley, 1993]. A common way of examining both the beam diameter and profile is by using low energy to irradiate a suitable material; the etched sample is then analysed to measure the diameter and observe the profile. This is an indicative method especially when the process is thermal. Alternatively, beam profile and homogeneity is monitored using a beam profiler which shows the shape of the beam, in real-time, during a process.

Laser-matter interaction (Laser processing)

The wave-particle duality concept is quite useful in treating laser-matter interaction. For example, laser generation is better described using the quantum (or particle) approach while propagation and delivery is suitably described using the wave concept. For laser-matter interaction, it is appropriate to use quantum physics. Thus viewing the beam as a packet of photons hitting the matter with which it is interacting. When the laser beam strikes the material, the photon energy is transferred to the material and subsequently converted to other forms of energy depending on the material. With metals, this is transferred to the mobile electrons which results in the heat energy that can cause vaporisation and disintegration of the metal. However, with non-metals, the energy can either be converted to chemical energy required for bond-breaking or heat energy for vaporization. These two possibilities depend on the type of material, its bond energy and the wavelength of the laser or more precisely the photon energy. Essentially, there are two common mechanisms for laser material interactions, which can occur at varying degrees while processing a material.

- Thermal (photothermal or pyrolytic): This is an electronic absorption in which the photon energy is used to heat up the material to be processed and thus part of the material is removed as a result of molecule vaporization, such as in CO_2 laser cutting. This type of process is broadly referred to as laser micromachining.
- Athermal (photochemical or photolytic): This is a photochemical process whereby the material is ablated by direct breaking of molecular bonds when hit by photons (energy) of the incident beam. In principle, this is only possible if the photon energy is equal or greater than the bond energy of the molecules of the material to be processed. During this process, a particular area of the surface of the material is removed with minimum (or without any, theoretically) thermal damage to the surrounding material. This process is generally called ablation, though photothermal processes are also referred to as ablation. Ablation is generally used in reference to polymer and/or soft materials, but laser ablation is also possible with other materials such as ceramic and glass. However higher fluencies are required in their case.

The etch rate – the amount of material removed per pulse – is mainly a function of the photon energy and the material being processed. However, it is impractical to model laser-matter interactions based on the aforementioned two quantities as the mechanism is also influenced by numerous other factors (e.g. thermal diffusion, absorption saturation, surrounding medium, etc.) such that the measured ablation depths seldom agree with these predictions; this necessitates more complex 'models' often based on these two quantities [Tseng, et al., 2007]. Equations 1 & 2 provide two often referenced mathematical representations: Beer's law and the Srinivasan-Smrtic-Babu (SSB) model [Shin, et al., 2007], which are based on pure photochemical and combination of photochemical and photothermal mechanisms respectively. The two formulae are similar except that SSB's adds a photothermal part to Beer's model where L, β, f and f_{th} are the etching depth per laser pulse, coefficient of absorption (cm^{-1}), laser fluence per pulse (J/cm^2) and threshold fluence (J/cm^2) respectively.

$$L = {}^{1}/_{\beta}\, ln\left({}^{f}/_{f_{th}}\right)\ for\ f\ >\ f_{th} \tag{1}$$

$$L = {}^{1}/_{\beta}\, ln\left({}^{f}/_{f_{th}}\right) + photothermal\ for\ f\ >\ f_{th} \tag{2}$$

2.1.1 Beam profile

The most common laser beam profile is the Gaussian beam (TEM$_{00}$ or fundamental mode) schematically shown in Figure 2a. Its beam intensity variation can be described according to equation 3, where I_0 = $I_{\max}$ = intensity at the centre of the profile, I is the intensity at any other point, and r is the radius of the beam taken at a point where the beam axis intensity has fallen to $1/e^2$ of its maximum. Although this Gaussian profile is better than and preferred to higher order modes, its intensity variation is still a source of concern in laser material processing and particularly in laser ablation. For this reason, a modified version - which is thought to improve the tapering of the beam profile - is generated with uniform intensity across the entire profile similar, in principle, to that shown in Figure 2b. This is described as a 'top-hat' (or 'flat-top') profile perhaps due to the 'flatness' of the top of the profile. As shown in Figure 2c, a top-hat profile is obtained from its Gaussian counterpart by taking the energy from the weak intensity region, where beam intensity distribution is lower than $1/e^2$ (i.e. 13.5 %) of the centre and folding it back into the region within the beam waist. A point should be made here: saying that a laser operates in a single mode e.g. TEM$_{00}$, simply means that this is the dominant mode of operation just like a given wavelength implies the fundamental (i.e. dominant) wavelength of operation.

$$I = I_0 e^{-({}^{r}/_{r_0})^2} \tag{3}$$

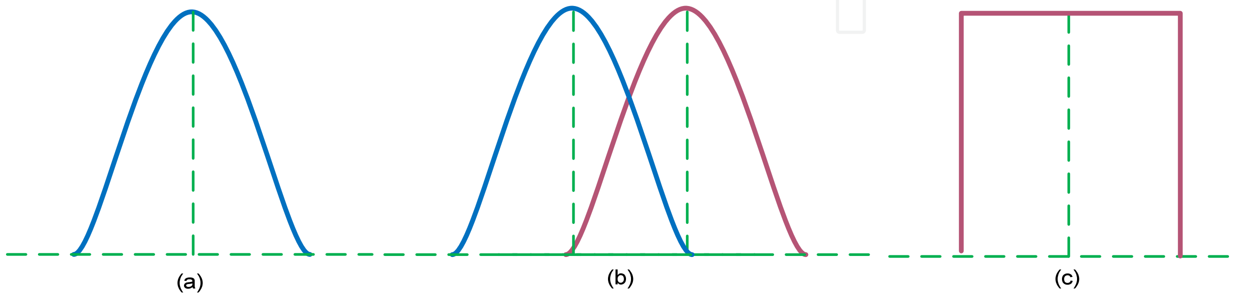

Fig. 2. Typical laser bean profile (a) Gaussian beam profile, (b) overlapping of Gaussian profile to generate 'top-hat', and (c) 'Top-hat' beam profile.

2.1.2 Ablation threshold

The ablation threshold is the point at which the applied energy density is enough to cause ablation either photolytic or pyrolytic. The value of this varies from polymer to polymer depending on the nature and strength of the bonds in the polymer and also on laser wavelength (Tables 1 & 2). An ablation threshold can be obtained from a plot of etch rate against a logarithmic scale of fluence at zero ablation rate [Jackson, et al., 1995; Tseng, et al., 2007]. Zakariyah (2010) obtained a threshold as the x-intercept value on a graph of ablation rate against incident fluence. Irrespective of the base of the logarithmic scale taken, the two approaches are found to produce the same value. Table 2 shows a list of common bonds in polymers with their respective bond energies, which need to be overcome during any laser ablation regardless of the nature of the mechanism. For photochemical ablation, the laser wavelength has to be carefully chosen such that the photon energy obtained from the laser is equal or greater than the bond energy of the polymer to be processed. When working below this threshold, no ablation is expected to occur, however, the chemical properties of the materials are subject to certain changes. Furthermore, operating at well above the threshold can cause or increase the heat-affected zone (HAZ) and debris deposition. The former is due to high energy while the latter is as a result of bombarding the ejected materials. It should be noted that intense bombardment of ejected particles above the ablation zone can retard the ablation rate. This is because the ejected materials might absorb fractions of the incoming beam thus reducing the effective fluence at the ablation zone. Wavelength is one of the factors that determine the thresholds of ablation. For example, the ablation threshold for PMMA (PolyMethyl MethAcrylate) is ~150 mJ/cm^2 at 193 nm and ~500 mJ/cm^2 at 248 nm – this is a 3-time increase in value between the two wavelengths. The rule-of-thumb for laser ablation of polymers is to have lower threshold fluences for ablation at shorter wavelengths [Pfleging, 2006].

Material	Fluence (mJ/cm^2)	λ (nm)	Material	Fluence (mJ/cm^2)	λ (nm)
PS	15.3	193	PMMA	150[1]	193
PET	18.4	193	Silicon nitride	195	-
Truemode™ acrylate polymer	20	248	SiO$_2$	350	-
PC	21.5	193	PMMA	500	248
PI	25.1	193	Nd:glass	500	193
Photo resist	30	-	Nd:YAG	800	193
PC	40	-	Glass, metal oxide	700-1200	-
PI	~ 40	248	Nd:YAG	1200	248
PI	50	308	Nd:glass	1600	248
PI	100	355			

Table 1. Ablation threshold fluence for some selected material [Chen, Y-T., et al., 2005, Jackson, et al., 1995; Meijer, 2004; Pfleging, 2006; Yung, et al., 2000; Zakariyah, 2010; Zeng, et al., 2003].

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[1] A threshold of 33.8 mJ/cm^2 is reported for PMMA at 193 nm by Chen, Y-T, et al. (2005)

Group	Bond Energy (eV)	Group	Bond Energy (eV)
C = C	7.0	O-H	4.5
C = O	6.7, 4.2	H-H	4.6
Si-Si, Cl-Cl	1.8 – 3	O-O	5.1
C-H	3.5	C-C	6.2
C-N, C-C	3 – 3.5	C-O	11.2
-N = N	3.5, >4.8	Benzene Ring	4.9, 6.2, 7.75

Table 2. Table showing typical bonds in photopolymers and their respective bond energies [Basting, 2005; Crafer & Oakley, 1993; Meijer, 2004; Tseng, et al., 2007].

2.2 Industrial laser – Excimer

Lasers can be classified based on a number of factors e.g. active medium (solid, liquid and gas), output power (low, medium and high power lasers), excitation method (electrical, optical and chemical), operating mode (continuous wave, pulsed mode and Q-switched output mode), efficiency and applications. CO_2, Nd:YAG and excimer lasers, with Ti-Saphire following suit, are the key lasers in material processing due to their relatively high power. These three form a complete laser assembly in PCB (printed circuit board) manufacturing processes. Excimer laser is described here as it is the prominent laser candidate for polymer waveguide fabrication; however, a UV Nd:YAG has recently been reported [Zaakriyah, et al., 2011] as a competitive alternative.

An excimer laser - a commonly used gas laser and the halide of noble gases – obtained its name from the contraction of the term 'EXCIted diMER'. Because a dimer strictly refers to a molecule composed of two similar subunits (ions, monomers, etc.), it is therefore more technical to refer to excimer as 'exciplex' meaning EXCIted comPLEX. The wavelengths of excimer lasers vary from about 190 nm (deep UV) to 350 nm (near UV)[2] (Figure 3) but ArF, KrF and XeCl are the most commonly used. F_2 ($\lambda = 157$ nm) laser is sometimes classified as a gas laser and sometimes as an excimer laser as implied in [Basting, et al., 2002; Tseng, et

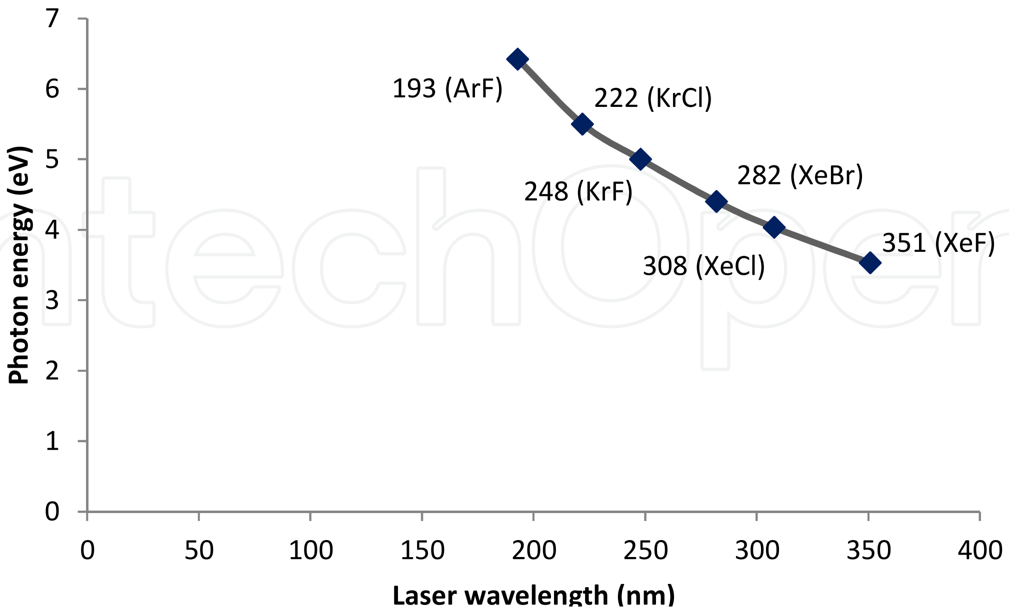

Fig. 3. A graph of photon energy (eV) against excimer laser wavelengths.

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[2] Basting, et al., (2002) put the range between 126 nm and 660 nm (visible region).

al., 2007]. The pulse duration and repetition rate are in the ranges of 5 – 50 ns and 1 – 100 Hz respectively.

Since its discovery and introduction into the market in 1970 and 1977 respectively, the excimer laser has turned out to be a multi-purpose, multi-featured laser with increasing market shares in industrial and medical applications. Its first commercially available product from Lamda Physik is called EMG 500 [Basting, et a1., 2002]. Although other lasers such as YAG and CO_2 lasers are also extensively used in High Density Interconnection (HDI) technology, the excimer laser ablation is indispensable when it comes to 'fine' finish micro- and nano-fabrications. This is particularly true for hard and delicate materials. This is largely due to its wavelength, pulse duration, and of course its pulse energy allowing for what is generally termed as a 'cold ablation' process. The excimer laser also excels others in its ability to 'mask-project' patterns, using stencil or metal-on quartz masks [Tseng, et al., 2007], on to a sample with a minimal HAZ. The minimal HAZ is argued to be due to the short interaction between the laser beam and the material. In addition, the short pulse duration of the excimer is also a contributing factor. Nevertheless, picosecond and femtosecond lasers are now available today. These classes of lasers are designed to further reduce the HAZ. They are also characterized by higher etch rate, strong absorption by the material, improved surface roughness and lower ablation thresholds [Li, L., et al., 2011; Sugioka, et al., 2003].

These aforementioned features of the excimer laser have attracted and favoured its use not only for polymers [Wei & Yang, 2003] but also with other materials such as ceramics [Ihlemann, 1996], glasses [Tseng, et al., 2007] and silicon [Li, J. & Ananthasuresh, 2001] which are often hard to machine. Besides, excimer lasers are now used for surface modification of various materials. Pfleging, et al. (2006) have used excimer at fluences below the ablation threshold to fabricate single mode optical waveguides in PMMA similar to that employed using CO_2 laser in [Ozcan, 200 8]. Thomas, et al. (1992) also used an excimer laser to effect changes to the chemical structures of materials (polymer and ceramic) with potential application in enhanced material adhesion and surface wettability among others.

3. Polymer waveguide fabrication for optical interconnect on PCB

3.1 Optical Interconnects (OI)

The miniaturisation in consumer electronics, dictated by the rise in demand for more features and the change in the manufacturing technology, has caused an increase in the data rate on the micro-levels such as backplane, board-to-board, and chip-to-chip. The bottleneck for copper transmission in PCB with high interconnection density and high-frequency is more pronounced at the 10 Gb/s limit where problems such as crosstalk, electromagnetic interference (EMI) and power dissipation, inter alia, cannot be tolerated [Holden, 2003; Offrein, 2008; Shioda, 2007]. To overcome this barrier, optical interconnect – as it has been successfully used for long haul communication - is being considered. The deployment suggested here is not to overhaul traditional copper technology but to create a hybrid electric-optical interconnect.

To address the bottleneck caused by the inherent problems in the copper transmission used in backplanes and boards, the last two decades have witnessed vigorous research input and output from researchers around the world to deploy OI on PCB. Japan, the EU and Asia-Pacific/North America, who led in the microvia technology, are also key figures in the OI deployment [Holden, 2003; Lau, 2000; Shioda, 2007]. Undoubtedly, the cost-effectiveness of OI is a major consideration if it is to be implemented [Huang, et al. 2003]. Hopkins & Pitwon (2007) asserted that at higher bandwidth for current and near future requirements for telecom and datacom systems, the application of OI at the backplane is unavoidable. It was argued that the cost of solving the bottleneck of copper transmission will surpass that of implementing OI at ~ 6.25 Gb/s (Fig. 4). Furthermore, the total power loss, commonly referred to as power budget, is also a consideration and is currently being investigated. It is written in [Uhlig & Robertson, 2005] that a ~20 dB would be an acceptable total loss for an optic link at the backplane; Dangel, et al. (2006) put this at 12 – 15 dB for board-to-board optical link of 30 – 100 cm. Uhlig and Robertson (2005, 2006) argued that at some point along the transmission, optical amplification would be needed for a realistic OI on PCB to be implemented. While optical loss is important, reliability (thermal cycling, athermal aging, high temperature reflow, environment, humidity tests, etc.) is another key characteristic and requirement for the deployment of the polymer waveguide [Dangel, 2006; Hwang, et al., 2010].

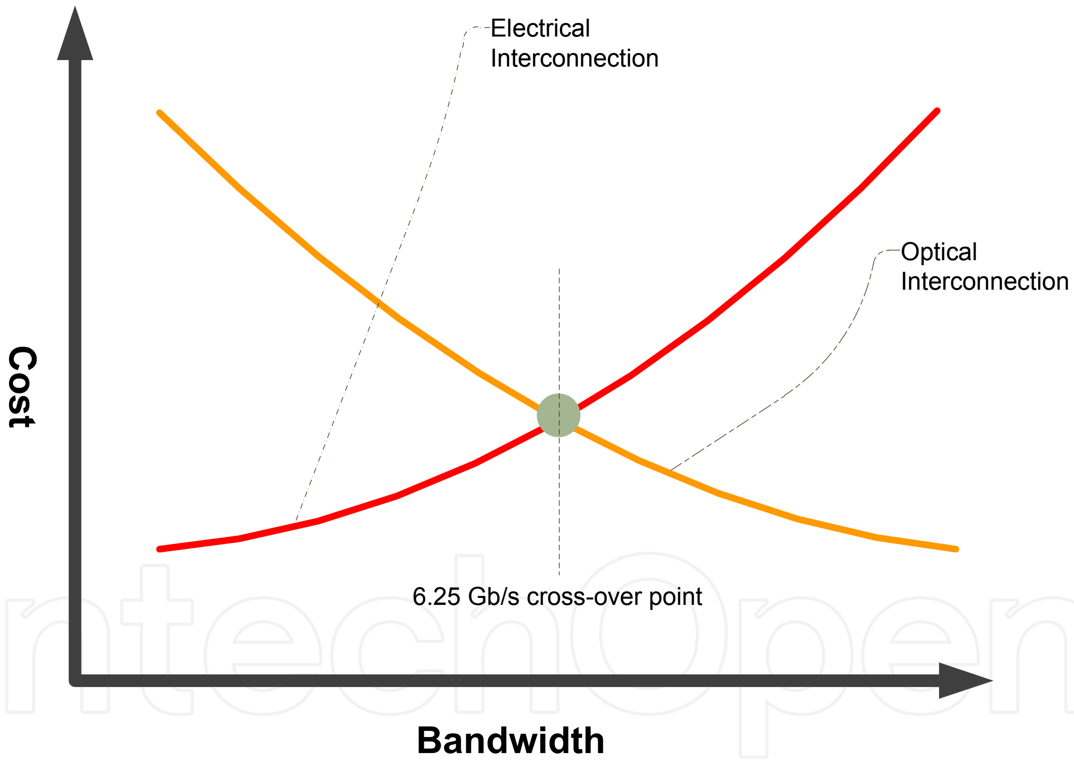

Fig. 4. Relative cost of copper technologies as compared to optical technologies on PCB [Adapted from Hopkins & Pitwon, 2006].

The two OI approaches under consideration are either unguided or guided; both having their pros and cons. The latter can be further divided into fibre- and polymer-based technologies with silicon-based waveguides also gaining momentum (Figure 5). Current literature reports suggest that a polymer-waveguide is the favoured candidate. This is because: (i) polymers are relatively cheap, (ii) low acceptable loss is achievable with polymer, (iii) they are easily available, and (iv) most importantly, polymer waveguide fabrication which is being considered, is compatible with the standard processes employed in PCB manufacturing such as soldering temperature, Coefficient of Thermal Expansion (CTE) matching, thermal stability and stress during lamination [Tooley, et al., 2001].

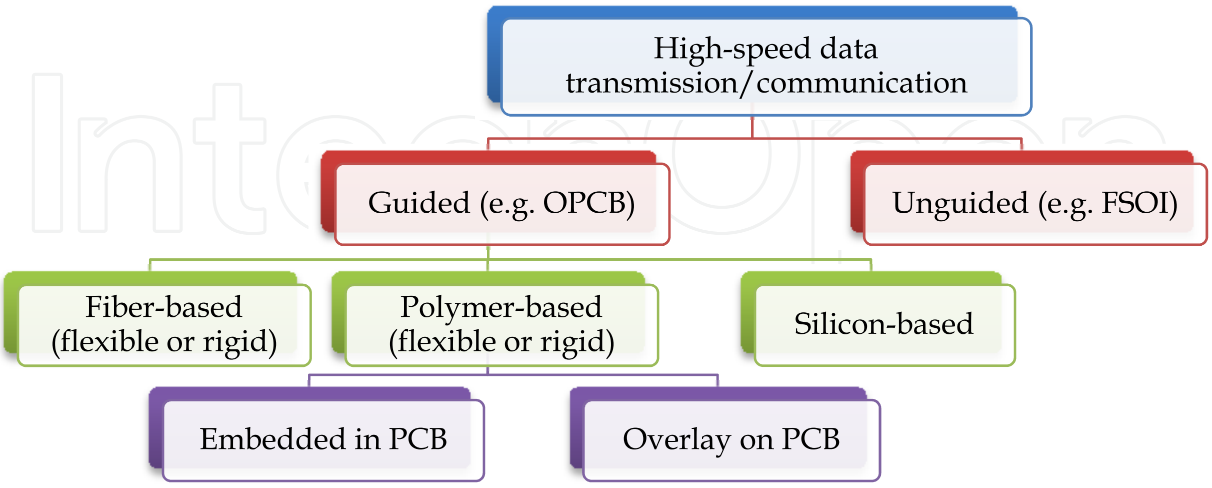

Fig. 5. Hierarchical classification of optical data communication system based on medium of transmission.

3.2 Deposition of optical polymer

The stages involved in laser ablation of a polymer waveguide are typified in Figures 6 and 7. In the first stage, liquid optical polymer is spun on FR4 substrate and subsequently UV cured to form both the lower cladding and the core layers. The samples were then dried in an oven (at 80 ^{0}C – 100 ^{0}C for about for about 60 minutes for Truemode™ acrylate polymer, $\Delta n \approx 0.03$ variable @ 850 nm) to ensure they were moisture-free. Laser ablation is carried out in the second stage to machine channels such that a ridge of polymer is left in-between the channels to form the waveguide. For one or more adjacent waveguides, the number of grooves required is equal to (n+1), where n is the number of adjacent waveguides. Finally, a layer of upper cladding is deposited using spin coating (or any other suitable coating technique) and then UV cured.

A single layer of waveguide fabrication is common as this is currently enough to provide the data rate requirements for OI, but a multilayer waveguide has also been demonstrated [Hendrickx, et al., 2007a, 2007b; Matsuoka, et al., 2010]. Multimode waveguides are also common; dimensions such as 20 µm × 20 µm, 30 µm × 30 µm, 35 µm × 35 µm, 45 µm × 45 µm, 50 µm × 50 µm, 50 µm × 20 µm, 70 µm × 70 µm, 75 µm × 75 µm, 85 µm × 100 µm have already been reported [Albrecht, et al., 2005; Bamiedakis, et al., 2007; Dangel, et al., 2004; Immonen, et al., 2005, 2007; Liang, et al., 2008; Tooley, et al., 2001; Van Steenberge, et al., 2004; Zakariyah, 2009, Zakariyah, et al., 2011]. Two or more adjacent waveguides with a pitch of 250 µm [Albrecht, et al., 2005; Horst, 2009; Hwang, et al., 2010; Kim, et al., 2007; Van Steenberge, et al., 2004] is preferred as it is the pitch used for Vertical Cavity Surface Emitting Lasers (VCSEL) and photodetector arrays, but other pitch sizes such as 80 µm [Dangel, et al., 2007], 100 µm [Dangel, et al., 2004] and 125 µm [Matsuoka, et al., 2010; Van Steenberge, et al., 2006] have also been used. Since the optical link required for OI is relatively short, loss due to multimode is acceptable and that alignment between various optical components would be relaxed. However, single mode waveguides is much suitable with silicon-based waveguides due to their high refractive indices, though they still pose alignment challenges [Horst, 2009]. Papakonstantinou, et al. (2008) reported a low cost method of achieving high alignment accuracy.

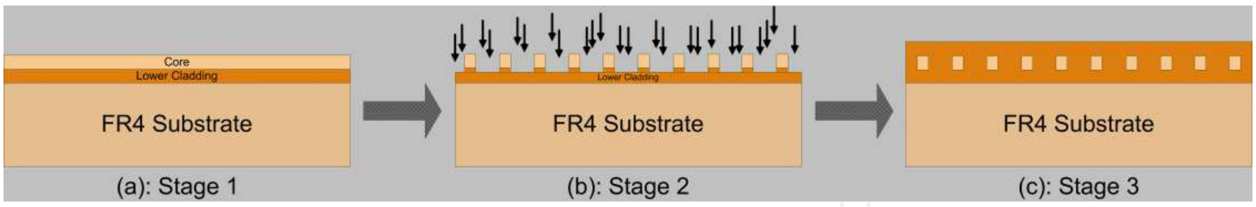

Fig. 6. Schematic diagram (side view) of the three major stages in the fabrication of optical waveguides by laser ablation.

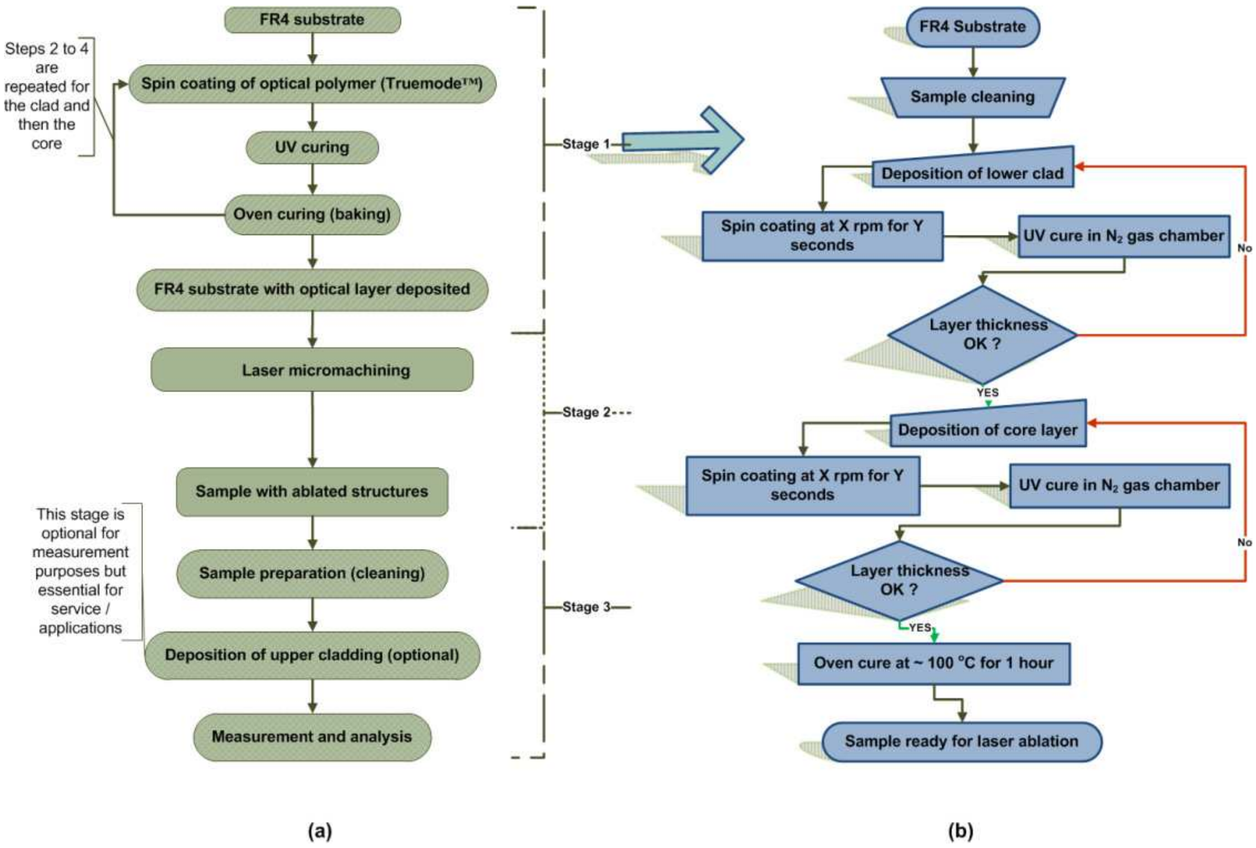

Fig. 7. (a) Flow diagram of the processes involved in patterning optical polymer waveguides using laser ablation, and (b) Schematic flow diagram showing procedure for depositing optical polymer on an FR4 substrate.

3.3 Laser ablation of polymer waveguides

Polymer waveguide fabrication for optical-PCB applications has been reported using a number of techniques, and more methods are still emerging. Selviah, et al. (2010) reported the use of four techniques - photolithography, laser direct writing, inkjet printing and laser ablation - in a flagship entitled '*Integrated Optical and Electronic Interconnect PCB Manufacture* - OPCB'. However, excimer laser ablation of optical waveguides is an emerging and competitive approach as it involves fewer steps when compared to others with great flexibility in pattern design. Furthermore, laser micromachining is currently being used for the drilling of vias for blind, buried and through holes in PCB manufacturing making it a more suitable choice when compatibility issues are taken into consideration. The key feature of this class of laser i.e. excimer is its wavelength and pulse duration. The latter reduces the degree of thermal diffusivity while the former is a key to high-energy intensity, high resolution and absorptivity of the laser beam not only in the polymer but also in tough materials such as glass [Tseng, et al., 2007]. The pulse duration of excimer laser is of significance when it comes to quality because shorter pulse width lasers give better machined quality though it is a costly task quality though it is a costly task [Chen, X. & Liu, 1999]; it also helps in reducing the ablation threshold [Ihlemann, 1996]. In fact most of the close competing lasers, for example YAGs and Ti-Sapphire, are found to operate in the UV regions and/or with very short pulse duration, thus intensifying competition.

The suitability of a UV laser (e.g. excimer) for a photochemical ablation over any other laser operating in the IR (or visible) region of wavelengths, such as CO_2, could be demonstrated as follows. The photon energy is given by $E = h\nu$, which is inversely proportional to its wavelength, thus a CO_2 laser operating at 10.6 µm will produce an energy more than 40 times less than that produced by a 248 nm KrF laser. Obviously, this is not in the order of magnitude of the energies for chemical bond scission of typical polymers, usually between 3 – 8 eV [Tseng, et al., 2007]. Increasing the number of pulses to match the required bond energy will merely result in a cumulative heat effect on the polymer surface. It is thus clear that excimer lasers have the right order of photon energy to athermally ablate polymers, while on the other hand, IR laser sources have photon energies much lower than 3 eV causing the dominance of a thermal mechanism. Therefore, in principle using the aforementioned assertion, laser of a maximum wavelength of 414 nm is required in order to photochemically ablate a polymer material with a bond energy of 3 eV. There would be a shift in the dominance of the mechanism by changing the wavelength of the laser source. For example, a shorter wavelength e.g. 355 nm would guarantee or increase the dominance of a photochemical process. On the other hand, a longer wavelength e.g. 1064 nm in the IR would not only reduce the dominance of photochemical but also initiate thermal process for the same polymer.

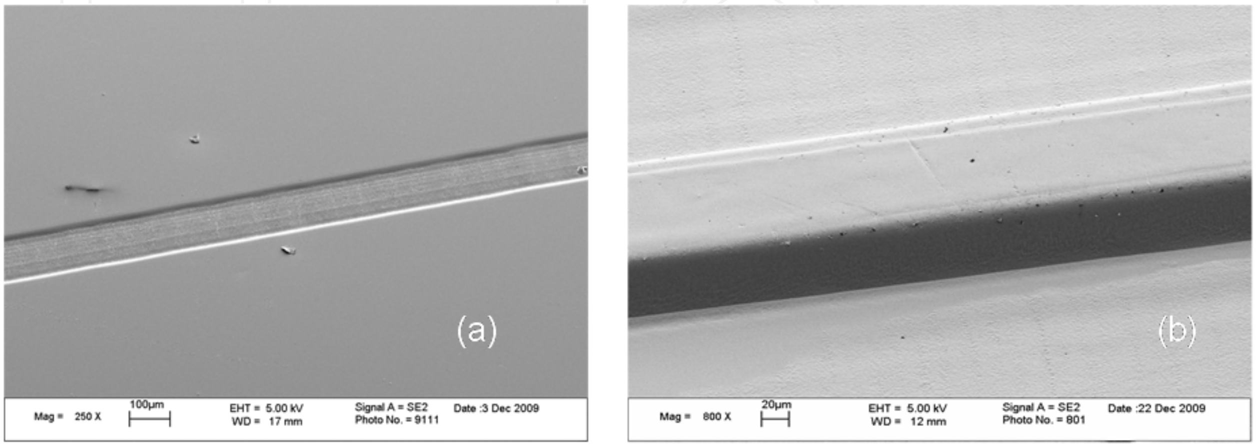

Fig. 8. Samples machined at 30 Hz, 50 shots per point and 3.6 mm/min with different fluences of 80 mJ/cm^2.

In Figure 8a above, a straight, shallow track is machined in an acrylate-based photopolymer while in Figure 8b above, two parallel tracks were etched leaving a ridge that constitutes a waveguide. In this case no upper cladding (as per stage 2, Figure 6) is applied. Sometimes, the ridge or waveguide may not be continuous. To examine this, light can be passed into one end of the guide for possible detection at the other end i.e. backlighting, as shown in Figure 9 where a single multimode waveguide of 50 µm × 35 µm and 60 mm long was illuminated from behind using a Flash™200 optical measuring device. The structure was made by ablating ~200 µm wide grooves in Truemode™ polyacrylate. Furthermore, waveguides can be 'crossed' at 90 degree (Figure 10) or other shapes may be desired. While excimer laser ablated waveguides is favoured, UV Nd:YAG (λ = 355 nm) [Van Steenberge, et al., 2004; Zakariyah, et al., 2011] and 10.6 µm CO_2 [Zakariyah, 2010] have been demonstrated as promising candidates especially for mass production at a low-cost.

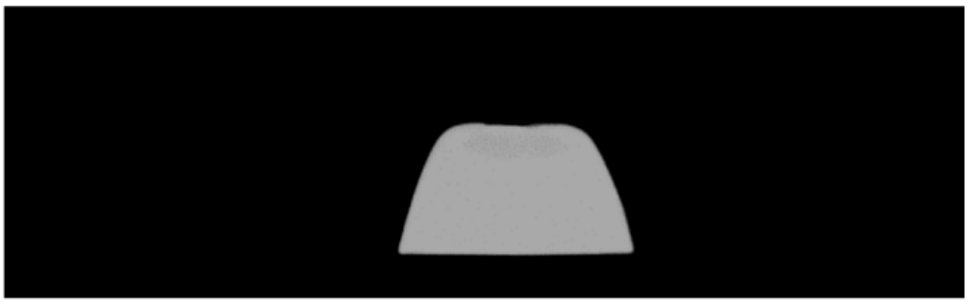

Fig. 9. Excimer laser ablation of optical waveguide showing cross-section of a 50 µm x 35 µm multimode waveguide in Truemode™.

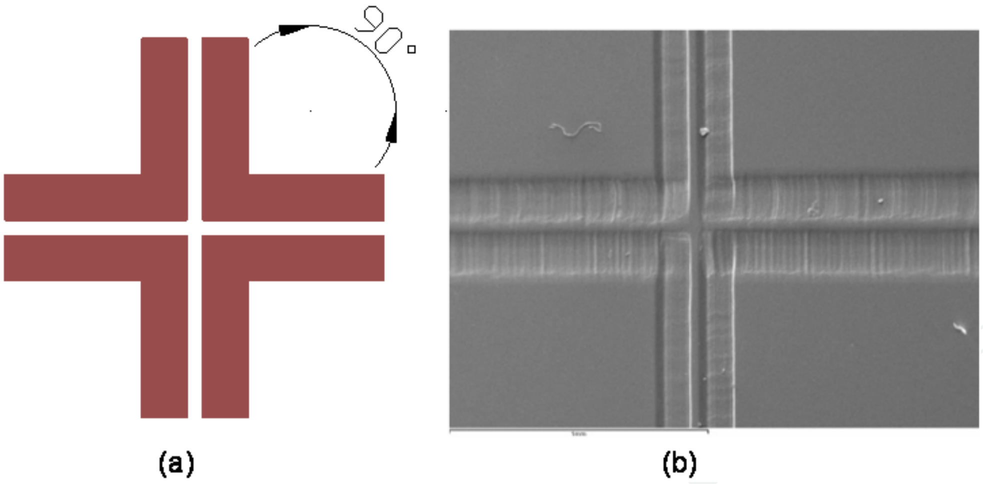

Fig. 10. Waveguides crossed over at 90 degree to each other machined at 100 mJ/cm2, 45 shots per point, 3.3 mm/min, 25 Hz and a single pass showing (a) a schematic diagram, and (b) an SEM image of an initial trial.

3.4 Integrated mirror fabrication

Optical signals on PCBs need to be routed to different parts of a device, such as between the boards of a backplane, if OI is to be fully utilised. Various proposals have been made on how to direct signals out of the plane of the board. These include 45-degree ended optical connection rods, microlens, 90^0-bent fibre connectors, 45^0-ended blocks, 45^0-ended I-shape waveguides, optical coupler and microprism. These aforementioned concepts of out-of-plane coupling utilises blade cutting, laser ablation, moulding, dicing and RIE among others with each having its benefits and limitations [Byung, et al., 2004; Cho, et al., 2005; Cho, 2005; Teck, et al., 2009; Van Steenberge, et al., 2006]. To improve the coupling efficiency, Glebov, et al.(2005) proposed a curved micro-mirror instead of the flat 45-degree commonly employed.

Coupling light in and out of the polymer waveguides could be achieved by relying on the air/vacuum refractive index which is capable of causing total internal reflection (TIR) (Figure 11a) at this interface as used in [Teck, et al., 2009], but this can be difficult in real application because: (i) a vacuum is not guaranteed in a typical electronics assembly, (ii) air content and temperature are subjects of the environmental conditions, and (iii) even if air refractive index is guaranteed to be constant, air reflectivity is not efficient for coupling. For these reasons, end facets of mirrors are coated with a metal to improve its reflectivity and for a good surface finish. The chosen deposition technique depends largely on the sample to be coated and adhesion adhesion inter alia. For example, the authors of [Glebov, et al., 2005] used sputtering to deposit a thin layer of gold on the mirror surface before filling the trench with upper cladding; similar process was used for laser ablated mirror [Van Steenberge, et al., 2006]. It should be noted that there is a potential of light scattering or reflection at the clad-core interface [Hendrickx, et al., 2007a, 2007b]. Furthermore, the inaccuracy of the fabricated mirror angle can cause a significant reduction in the amount of light emanating from the core-clad exit of the waveguide to that reaching the metallised mirror surface thus affecting the coupling efficiency; a short path with a minimum angle deviation can mitigate this challenge.

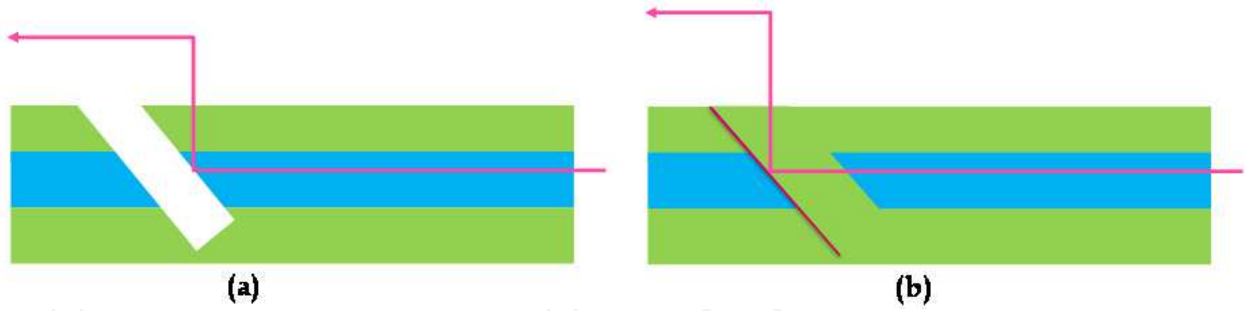

Fig. 11. Mirror fabrication schemes (a) TIR is used to deflect incoming signal out of the waveguide at the waveguide-air interface, and (b) light is coupled from a metal deposited at the surface of mirror trench which is the trench filled with cladding material.

While the out-of-plane coupling scheme is gaining impetus, there is no doubt that in-plane lateral routing of optical signals is also needed. A typical system architecture would require routing of signals not only from one layer to the other, but also within a layer; the latter would be extremely important if OI is extended to the board (and even chip) level as various roadmaps have laid down this possibility. Figure 12 is a schematic diagram of the in-plane mirror fabrication, which can be used to couple light between multiple components in the same layer. With this design, an effective turning angle of zero, 90-degree and multiples of 90-degrees are possible; a scheme demonstrated in [Glebov & Lee, M-G., 2006; Lamprecht, et al. 2009; Zakariyah, 2010]. Glebov & Lee, M-G. (2006) placed a vertical terminator at the end of the waveguide to form the mirror with a loss of 0.5 – 1.0 dB recorded for this approach; however, Zakariyah (2010) employed excimer laser ablation to manufacture the 45^0 lateral mirrors. It is argued [Zakariyah, 2010] that laser ablation is a more suitable fabrication technique as it allows for both the waveguide and the mirrors to be manufactured using a single process on the same system. The laser ablation approach was also used for out-of plane mirror coupling such as in [Teck, et al., 2009] for 3D out-of-plane coupling.

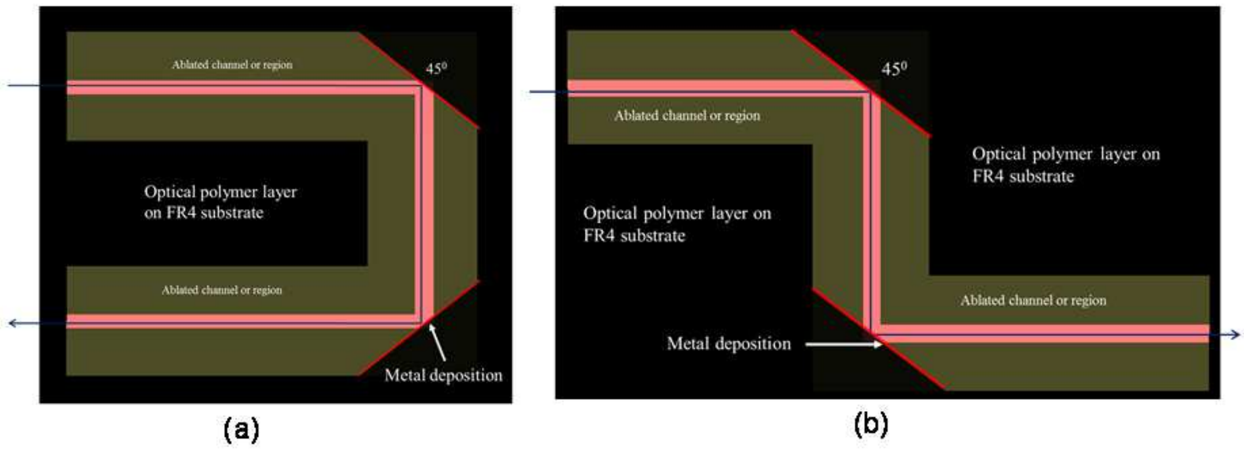

Fig. 12. Proposed 2D in-plane scheme showing (a) 45-degree in-plane coupling mirror design with 180-degree effective turning angle, and (b) 45-degree in-plane coupling mirror design with zero-degree effective turning angle.

3.5 Loss measurement

Signals launched at one end of an optical waveguide are not ideally identical in many cases to those arriving at the receiving end, either due to attenuation (change in amplitude) or distortion (change in waveform). These losses (propagation, coupling, angular misalignment, etc.) are quantified using a logarithmic unit called decibels (dB) using equation 4, where P_1 and P_2 represent the input and output power respectively. For a loss, it is a negative dB while a positive value indicates a power gain, usually obtained in amplifiers or amplification circuits. Sometimes the negative sign is omitted but replaced with 'loss' to mean attenuation in signal.

$$Loss\ (dB) = 10\log_{10}\frac{p_2}{p_1} \tag{4}$$

Reports have shown different values for the waveguide propagation loss depending mainly on the materials and the fabrication process used; Teck, et al. (2009) put the loss values in the range of 0.05 – 0.6 dB/cm, and the loss at a datacom (λ = 840 nm) in the range of 0.01 dB/cm – 0.8 dB/cm was given in [Holden, 2003]. Propagation loss of 0.24 dB/cm was recorded for a single mode waveguide in polyetherimide at 830 nm using laser ablation [Eldada, 2002]. A polymer waveguide manufactured by excimer laser ablation produced a propagation loss of 2 dB /cm at 1550 nm [Jiang, et al., 2004]; this high loss was attributed to the sidewall roughness of the guides. At 850 nm, propagation loss between 0.04 dB/cm and 0.2 dB/cm and 0.04 dB/cm and 0.18 dB/cm are reported for flexible and rigid waveguides respectively measured for different polymers [Shioda, 2007]. Table 3 is a list, though not exhaustive, of recent optical waveguide reports. While propagation loss is dependent on the waveguide characteristics, it is possible to reduce the insertion loss by reducing the coupling efficiency. One way of achieving this is through a good alignment between the coupling device and the waveguide. Jiang, et al. (2004) proposed an excimer laser ablation of the end facets for efficient coupling of light which in turn can reduce the loss.

Material	**Process**	**Waveguide Dimension**	**Loss**		**Reference**
			Waveguide	**Mirror**	
Custom multifunctional acrylate based photo-polymer	UV Laser Direct Writing (He: Cd, 325 nm and 3 mW)	50 µm × 50 µm multimode	< 0.17 dB/cm @ 850 nm & < 0.5 dB/cm @ 1300 nm	-	Tooley, et al., 2001; Walker, et al., 2008
SU-8-50 epoxy (core) & MR-L6100XP (cladding)	UV Lithography	85 µm × 100 µm	0.60 ± 0.03 dB/cm at λ = 850 nm	1.8 – 2.3 dB (estimated)	Immonen, et al., 2005
Perfluorocyclobutane (PFCB)	Rubber molding	47 µm × 41µm	0.4 dB/cm (1300 nm) & 0.7 dB/cm (1550 nm)	-	Lee, B-T., et al., 2000
Photosensitive polymer	UV photolithography	30 µm × 30 µm	0.06 dB/cm (850 nm) & ~ 0.25 dB/cm (1310 nm)	-	Matsuoka, et al., 2010
-	Imprinting	50 µm × 50µm	0.035 dB/cm (850 nm)	0.5 dB per each facet	Hwang, et al., 2010
Truemode™ acrylate-based photopolymer	Excimer Laser Ablation (3 ± 0.5 J/cm^2, 200 Hz & 240 µm/s ablation speed)	50 µm × 50 µm	0.13 dB/cm at 850 nm	-	Steenberge, et al., 2006
Polycarbonate (cladding) epoxy resin (core)	Hot-embossing	-	0.5 dB at 850 nm	-	Kim, et at., 2007
Polysiloxane-based polymer	Photolithography and dry etching	8 µm × 8 µm single mode	0.17 dB/cm at 1310 nm & 0.43 dB/cm at 1550 nm	-	Usui, et al., 1996
Truemode™ & ORMOCER	Photolithography and Excimer Laser Ablation	50 µm × 50 µm two layers	0.12 dB/cm at 850 nm	-	Hendrickx, et al., 2007a, 2007b; Steenberge, et al., 2006
Proprietary to Mistui Chemicals Inc., Tokyo, Japan	Excimer laser ablation (mirror)	70 µm × 50 µm	0.1 – 0.3 dB/cm at 850 nm	< 4 dB loss for two 45^0 82 mm long mirrors	Teck, et al., 2009

Material	**Process**	**Waveguide Dimension**	**Loss**		**Reference**
			Waveguide	**Mirror**	
UV curable resins (core)	Hot-embossing	60 µm × 60 µm	~ 0.1 dB/cm at 850 nm	-	Yoon, et al., 2004
Photopatternable polymer	Photolithography (WGs) & Microdicing (mirrors)	30 µm × 30 µm	0.05 dB/cm at 850 nm	0.5 – 0.8 dB at 850 nm	Glebov, et al., 2005, 2007.
Photosensitive acrylate polymer	Photolithography	50 µm × 50 µm (250 µm pitch) & 35 µm × 35 (100 µm pitch)	0.035 – 0.05 dB/cm at 850 nm & 0.12 dB/cm at 990 nm	-	Dangel, et al., 2004
ORMOCER	-	≤ 50 µm × 10 µm multimode	-	-	Uhlig, et al., 2006
Truemode™	UV Nd:YAG Laser Ablation	45 µm × 45 µm	1.4 ± 0.5 dB/cm at 850 nm	-	Zakariyah, et al., 2011
Polysiloxane	Casting + Doctor blade	-	0.05 dB/cm at 850 nm	-	Kopetz, et al., 2004.
Fluorinated acrylate polymer	Soft molding (core) & spin-coating (cladding)	70 µm × 70 µm	-	-	Liang, et al., 2008
Epoxy resin	Spin-coating	50 µm × 50 µm	0.15 dB/cm at 850 nm	-	Albrecht, et al., 2005
Siloxane polymer	Photolithography	50 µm × 20 µm	0.03 – 0.05 dB/cm at 850 nm	-	Bamiedakis, et al., 2007
SU-8 (NANOTM SU-8-50)	Photolithography	50 µm × 50 µm	-	-	Chen, Y-M, et al., 2005
Deuterated PMMA (core) & UV-cured epoxy resin (cladding)	Spin coating, photolithography & RIE	40 µm × 40 µm	< 0.02 dB/cm at 830 nm	0.3 – 0.7 dB	Hikita, et al., 1998

Table 3. Optical polymer waveguide fabrication techniques

4. Conclusion

In this chapter, the author presented the need for OI for both intra- and inter-board applications due to prevailing limitations with electrical interconnection on the PCB despite the various rectifying measures being considered. For successful implementation of OI, the following are needed: materials that would be compatible with PCB manufacturing procedures; fabrication techniques that would be easy, cost effective and efficient from the production point of view; and finally materials / waveguides that would satisfy the optical power budget requirement. A polymer-based waveguide is favoured for this technology primarily due to its low cost and compatibility. Multimode polymer waveguides with typical dimensions 50 ± 20 µm square are common as it relaxes alignment constrain thus lowering coupling. While various fabrication techniques have been reported with new still emerging procedures, laser ablation is a preferred approach since it is the technique currently being used for the drilling of µvias, which makes it a much compatible candidate. Furthermore, for the fabrication of integrated mirrors, either in-plane or out-of-plane, laser ablation using an excimer laser for example, is a much suitable option for this due to its excellent laser matter interaction, resulting in clean removal at micro-level scales. In addition, the mask projection available with excimer laser makes it possible for complex features to be easily defined. Although the cost and speed of excimer laser could be an issue from the production point of view at this stage of the deployment, other lasers such as UV Nd:YAG and CO_2 can offer both prototyping and mass production opportunities as it has been demonstrated, thus making laser ablation an all-encompassing technique meeting required production speed, cost, efficiency and quantity. In light of this, the chapter also provides an overview of laser technology for material processing and in particular for polymer waveguide fabrication.

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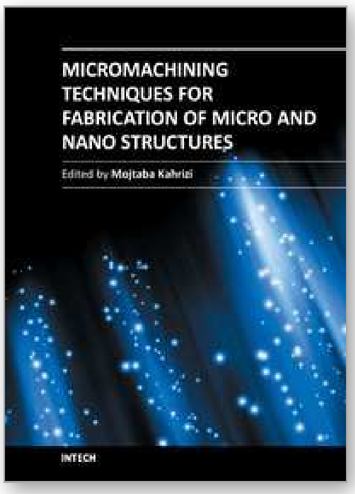

Micromachining Techniques for Fabrication of Micro and Nano Structures

Edited by Dr. Mojtaba Kahrizi

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Micromachining is used to fabricate three-dimensional microstructures and it is the foundation of a technology called Micro-Electro-Mechanical-Systems (MEMS). Bulk micromachining and surface micromachining are two major categories (among others) in this field. This book presents advances in micromachining technology. For this, we have gathered review articles related to various techniques and methods of micro/nano fabrications, like focused ion beams, laser ablation, and several other specialized techniques, from esteemed researchers and scientists around the world. Each chapter gives a complete description of a specific micromachining method, design, associate analytical works, experimental set-up, and the final fabricated devices, followed by many references related to this field of research available in other literature. Due to the multidisciplinary nature of this technology, the collection of articles presented here can be used by scientists and researchers in the disciplines of engineering, materials sciences, physics, and chemistry.

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