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The integration of optical interconnections on ceramic substrates

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Keywords
Optical interconnection, ceramic substrate, alumina, aluminium nitride, optical fibre, laser microprocessing, V-groove

Abstract
High heat conductivity and high heat capacity makes ceramic substrates indispensable to the manufacture of Multi-Chip Modules (MCM) and power electronics. In this paper a detailed description of the integration process of optical lines on to ceramic substrates is presented. The manufacturing of microgrooves in ceramic substrates and the process of integration of optical fibres and active elements is described. Coupling active elements to optical fibre is also presented. Through such an integrated optical line a 4Gb/s signal was transmitted.

Introduction

Many people believe that replacing electrical cables with optical fibres will solve many of the problems associated with the transmission of signals with GHz frequencies. This is reflected in the number of articles [1-4] and books concerning the introduction of optical interconnects into VLSI circuits [5-8]. The optical connections found in Integrated Systems (IS) divide into two groups: on-chip and off-chip. Many research programs involved in the development of optical interconnections began at the end of the twentieth century [9, 10]. These programs focused on the development of optical technology in both systems for use with Multi-Chip

Module (MCM), Printed Circuit Board (PCB) and between the modules found inside computers. Optical systems can be demonstrated that communicate with each other in free space [11]. Such systems have the advantage that they allow very high packing density and also by using a controllable micro-mirror, to switch light beams [12]. Unfortunately, a significant disadvantage of such free space communication is the difficulty in coupling entire optical systems [13]. Another option is to transmit signals through plastic optical fibres [14] or planar waveguides [15, 16]. Within the work carried out by six Japanese research centres [17] scientists integrated on to a 4.5 mm x 5 mm silicon substrate thirteen optical devices which included InGaAsP laser diodes, Mach-Zehnder modulators, multimode interference (MMI) splitters, silicon rib waveguides and a PIN type Ge diode. The system has achieved transmission rates of 5 Gb/s at a Bit Error Rate (BER) of less than 10^{-12}. Another solution was presented by researchers from the University of Cambridge [18], who realized, on a PCB, a demonstrator containing two layers of connections. On the upper surface of the substrate active elements (VCSEL, PIN photodiode made of GaAs, TIA amplifier) and multimode polymer optical fibre were distributed. On the bottom surface of the substrate metallic tracks and a layer of electrical connections were placed. The total power losses occurring in the optical path according to the authors reached approximately 8dB with a transmission of 10 Gb/s.

This paper presents the design process and realization of integration of optical interconnections on ceramic substrates. The multi-mode, bend-insensitive OM4 class optical fibre, described in the TIA 492AAAD standard, was chosen during the initial research [19]. The integration of the multi-mode optical fibre (MMF) as well as active elements (VCSEL and PIN diode) with ceramic substrates is also presented. Additionally the coupling of MMF to active elements by using angled ball-lensed optical fibre (ABLOF) is demonstrated.

Preparation of ceramic substrates for integration with optical interconnections

Ceramic substrates are used in the IS, thanks to their advantages such as: excellent mechanical and electroconductivity properties or relatively high thermal conductivity. Moreover they have similar thermal expansion coefficients to other common elements. A review of substrates commonly used in IS and their properties are shown in Table 1. Among ceramic substrates, the cheapest and most common substrates are based on Aluminium Oxide (Al_2O_3). Aluminium Nitride (AlN) substrates are used for more advanced MCM modules, and power electronics, and the remaining substrates are used less frequently due to the high price, and in the case of Beryllium Oxide (BeO) the toxicity of beryllium.

Table I The parameters of ceramic substrates used in electronics

Parameter	***Ceramic types***				
	96% Al_2O_3	*99,5% Al_2O_3*	*99% BeO*	*AlN*	*BeO/SiC*
Density [g/cm^3]	*3.7*	*3.9*	*2.9*	*3.3*	*3.2*
Coefficient of thermal expansion [ppm/K]	*6.4*	*6.6*	*5.0*	*5.6*	
Thermal conductivity	*35*	*37*	*250*	*170*	*270*

[W/mK]					
Flexural strength [MPa]	*220.8*	*338.1*	*131.1*	*300*	
Dielectric strength [kV/mm]	*8*	*9*	*14*	*20*	
Specific resistance x10^{14} (at 25^{0}C) [Ωcm]	*7*	*7*	*10*	*10*	*>0.1*

Selection of ceramic substrates

It is believed that the new generation of electronic packaging requires excellent thermal stability and heat dissipation to achieve maximum performance. Therefore our goal was realization of ceramic substrates, dedicated to MCM or Power Integrated Circuits (PIC) that have an integrated optical line. AlN and Al_2O_3 substrate materials have been widely used in high power module applications due to their high current capability, high heat dissipation, flexible patterning and high reliability [20, 21]. The popularity and excellent performance mentioned above informed the decision to choose AlN and Al_2O_3 substrates in our research. Both substrates dimensions were 50mm x 50mm x 1mm. For both these substrates integrated optical lines were made according to the design in Fig. 1. It is assumed that the height and the width of the microgroove were 280µm, to enable to integrate optical fibre with primary coating (diameter 250µm).

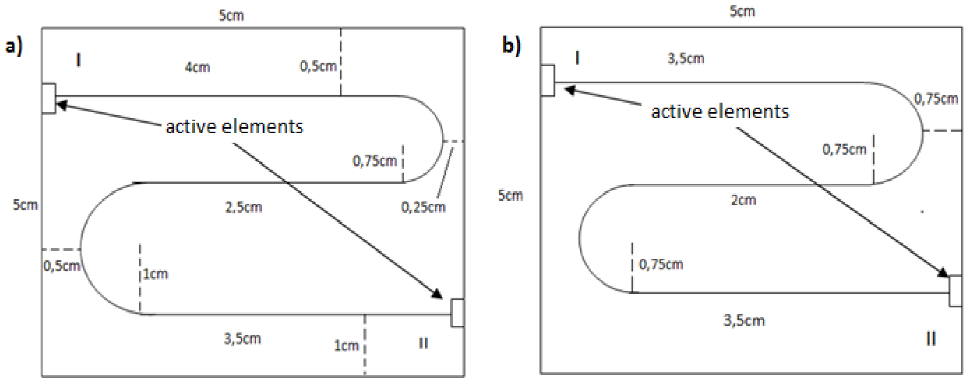


Fig. 1 Plan of ceramic substrates with: (a) asymmetric turns, (b) symmetric turns

Manufacturing of the microgrooves in the ceramic substrates

The substrates are fairly difficult to process using typical grinding techniques due to their very high hardness and brittleness, especially in the micro-scale [22, 23].Chemical etching is found to be ineffective [24, 25]. In this work, laser direct microprocessing was used to manufacture microgrooves in the Al_2O_3 and AlN ceramic substrates as an established technique to process ceramics [22, 23, 26, and 27]. All processing was performed using a 20W G4 EP-Z SPI laser. The laser specifications are:

- Wavelength: 1604nm;
- Maximum average power: 20W
- Beam quality: single mode, M^2<1.6
- Pulse duration: 3ns – 500ns is 5ns steps

- Frequency: 1kHz – 1MHz (depending on pulse duration)

The laser was connected to a GSI Lightning galvanometer scanner head and a 100mm F-Theta focussing lens was used to focus the laser beam (Fig. 2). The focused spot size is 29µm. The laser allows the changing of the laser process parameters, including pulse durations, 'on-the-fly' during the machining process.

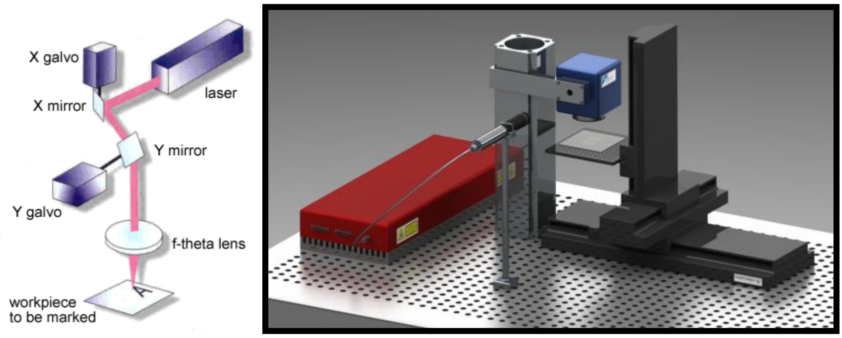


Fig. 2 The laser setup.

The aim of this work was to achieve high quality grooves with very exact sizes, including depth, and a smooth surface. Laser engraving techniques were used to achieve these project aims. The technique consists in filling the required shape with lines. If the distance between lines is smaller than the spot size it is possible to engrave the whole structure. All the tested parameters are presented in Table 2.

Table 2: Tested laser parameters

Parameter:	Value:
Average power	10W – 20W
Pulse durатation:	100ns, 200ns, 245ns, 320ns, 390ns, 490ns
Frequency	20kHz for 245ns – 490ns 27kHz for 200ns 41kHz for 100ns
Scanning speed	300mm/s – 1500mm/s
Hatching (line filling)	5µm – 40µm
Number of passes	40-120

It was found that:

- 245ns pulses (1mJ pulses) gave the best quality of edges and bottom surface; 390ns pulses achieved the highest removal rate
- Optimal hatching distance was 20µm, so the lines overlapped by about 50%
- Optimal scanning speed depended on frequency; pulse overlapping at the level of 40% gave the best surface and edge quality, typically this was 400mm/s

Based on the above conclusions it was decided to use a pair of engraving passes, one using 390ns to increase removal rate and the second one using 245ns pulses to improve surface and edge quality. Application of various engraving passes was enabled by changing laser parameters 'on-the-fly'. The final set of parameters was:

- Average power: 20W
- Pulse duration: 245ns/390ns
- Frequency: 20kHz
- Scanning speed: 400mm/s
- Hatching distance: 20µm
- Number of passes: 72

Additionally at the end of the process a few cleaning passes were undertaken to improve quality, and remove ablation products, using:

- Average power: 12W
- Pulse duration: 30ns
- Frequency: 500kHz
- Scanning speed: 3500mm/s
- Hatching distance: 11µm

The above parameters can be applied for Al_2O_3 substrates as well as AlN substrates. However, for AlN ceramic a laser with $M^2<1.3$ was chosen to achieve smaller spot size and higher power density. Moreover, on the AlN surface a thin layer of aluminium was created. Therefore the cleaning passes were applied with each pair of engraving passes.
The final results of the machined channels are shown in Fig. 3. The Leica DM4000 M LED was used to take photo presented in Fig.3b).

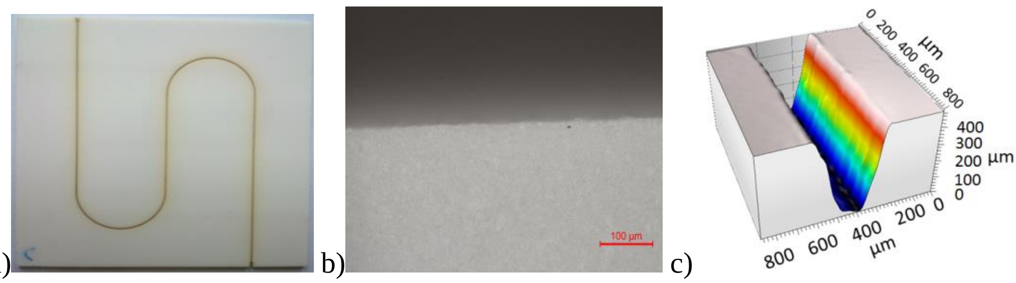
a) b) c)


Fig. 3 Laser made channels in Al_2O_3: a) overview b) edge quality c) profile

Integration of active elements on ceramic substrates

VCSEL lasers are very popular in high-speed optical communications. They have a low divergence beam with circular cross-section, are a well-developed technology and hence low cost. Therefore as a VCSEL laser, model 10 Gbps VCSEL-850 of Global Communication Semiconductor LCC, has been chosen for this work. The dimensions of the structure, important from the point of view of its integration with an opto-ceramic substrate, are 250 µm x 250 µm x 150 µm. The diameter of the contact area of the anode, located on the upper surface, is 75 µm and the cathode is on the bottom surface.
As very-fast receivers in optical communication, only two types of photoreceptors are usually considered: an avalanche photodiode (APD) or PIN diode. In APD by applying a high reverse bias voltage (typically 100-200 V in silicon), APDs show an internal current gain effect (around 100) due to impact ionization. They are more complex and expensive then PIN diodes. Therefore as a photodetector, a photodiode PIN model 4Gbps-GaAs was chosen. Its

dimensions are 450 μm x 300 μm x 100 μm. The diameters of the contact fields of anode and cathode are 100 μm, and the diameter of the photosensitive area is 70 μm. The installation of the active elements on to the ceramic substrates was carried out in two steps. In the first step the structures of the VCSEL and PIN photodiode were pasted into the slots made on ceramic substrates using the conductive glue Epo-Tek H20E. In the second step the active elements were connected with pads located on ceramic substrates using ultrasonic wire bonding. Pictures of a PIN photodiode integrated with a ceramic substrate are shown in Fig. 4.

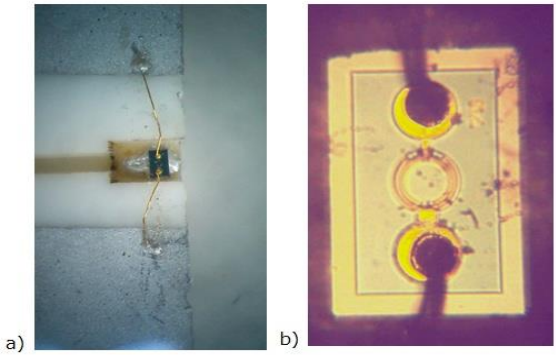


Fig. 4 (a) PIN photodiode integrated on ceramic substrate, (b) PIN photodiode with wire bonding

Coupling optical fibres to active elements

Angled-ball lensed optical fibres (ABLOF), shown in Fig. 5, have two main advantages: they allow a change in the direction of light propagation and have a larger numerical aperture (NA) that enables low collimation loss. ABLOFs were manufactured using a Furukawa S153 fusion splicer. The process and ABLOF parameters were presented in a previous paper [28]. The diameter of the lens was 230 µm ± 4 µm. Lenses were polished at the angle of 45 degree. In Fig. 6, a ceramic substrate with integrated PIN diode and optical fibre is shown. At the top of the lens the polished surface is clearly visible.

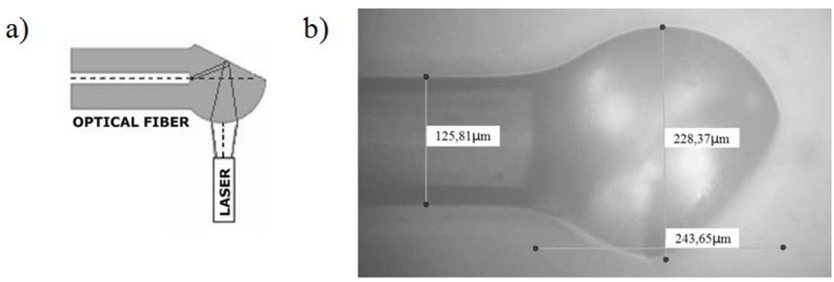


Fig. 5 (a) The idea of angled-ball lensed optical fibre, (b) angled-ball-lensed optical fibre

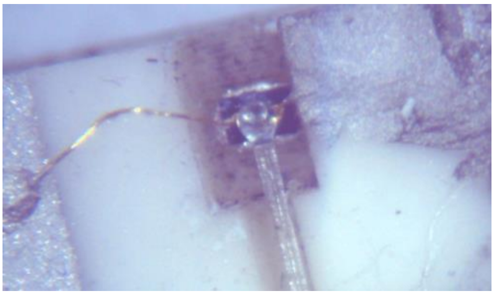


Fig. 6: Optical fibre coupled to 4Gbps-GaAs-PIN diode

The rest of the optical fibre was coated with a layer of cured enamel paste. The paste used was a powder enamel ASF 1700 (77%) slurry and an organic component (23%) as a 9% solution of ethyl cellulose N-22 in a solvent (butyl carbitol acetate, terpineol, dibutyl phthalate).

Results

Signals with a frequency of 1 GHz and 2 GHz were sent through the optical fibre system. The light source was excited with a continuous signal power level of 20 dBm. The spectrum analyser Signal Hound model USB-SA44B recorded the output of the line in the recording mode "max-hold". This means that the ratio of useful signal to noise, is illustrated for the worst case signal transmission. The spectra of the output signals from the PIN photodiodes integrated into the ceramic substrates are shown in Fig. 7. It can be seen that the difference between the noise level and the level of the useful signal is 13-15 dBm. From the point of view of ensuring the correct demodulation of the signal, these values are sufficient and will allow proper operation of the opto-electro (O/E) converters.

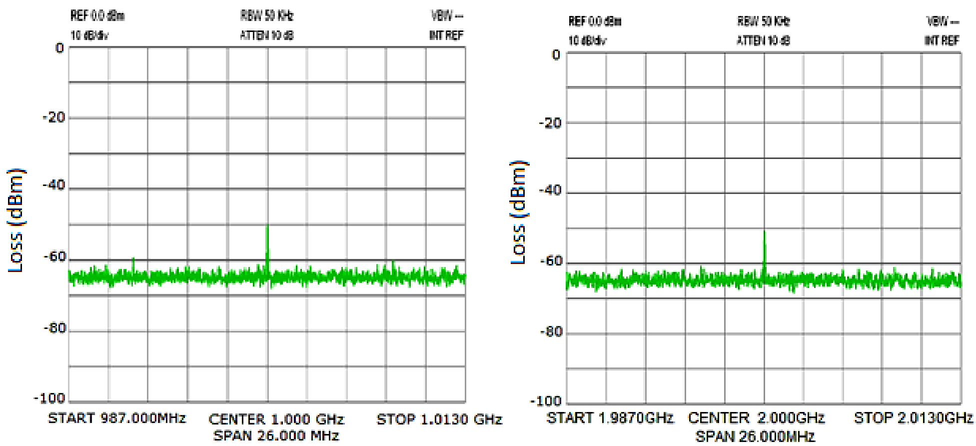


Fig. 7: The spectrum of a PIN photodiode output signal at a frequency of generator: (a) 1GHz and (b) of 2GHz

Conclusion

The integration of active and passive elements on ceramic substrates first required to choose the selection of the light source and detector. After selecting optimal active elements, the shape and size of V-grooves for OM4 BI MMF and places for active elements were designed for the ceramic substrates. Different studies were related to choosing the method of coupling the optical fibre to the VCSEL and photodiode. ABLOFs have been recognised as the most promising solution. Using ABLOFs significantly simplified the integration of active elements on to the ceramic substrate. Finally activity concentrated on the integration of active elements, MMF and ceramic substrates. The substrates were able to transmit optical signals at 2GHz frequency. Further investigation into the detailed characterization of the developed integrated optical line is required.

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