

High-quality CO₂ laser machining of LTCC structures for thermal management of a group of single-emitter laser diodes

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ABSTRACT

There has been recent interest in the use of LTCC (low temperature co-fired ceramics) technology as a platform for optical integration of both active and passive components because of its electrical, thermal and mechanical characteristics. Active components require methods for removing the heat generated without compromising the passive alignment of surrounding components. A thermal management structure for impingement water-cooling of a group of single-emitter laser diodes is reported, fabricated with CO₂ laser cut layers of LTCC to within tens of micron accuracy. We present a technique that uses precisely fitted, laser-cut nanocarbon layers to remove the problem of the collapse of internal water channels during isostatic pressure lamination. The structure provides 5 water jets to localize cooling under the diode laser chip, reducing thermal impedance.

Keywords: LTCC; thermal management; laser diodes

1. INTRODUCTION

Improvements in the electro-optic efficiency of laser diodes have given rise to compact, high-power beam sources with electrical-to-optical efficiencies between 50–75%. Today's laser diodes are capable of producing hundreds of watts of continuous wave (CW) output power and it is very common to find heat flux densities of >2 kW/cm² [1]. A variety of heat management methods have been used, from very small conductively-cooled packages to large arrays with internal micro-channel water-cooling. In this paper we develop a water jet cooler within a ceramic substrate using lamination of laser-cut LTCC and sacrificial filler layers. This development addresses the thermal management of multi-element single-emitter laser diodes in single packages by enabling internal water channel structures to distribute coolant.

A common solution for removing heat from a laser diode is to use copper micro-channel coolers (MCC). Unfortunately, MCC have problems with blockages due mainly to electrolytic corrosion and

erosion; as a result, a closed-circuit of deionised water is needed. In addition, there is CTE mismatch between GaAs (≈6.5 ppm/K) and copper (≈16 ppm/K). As an alternative to MCC, Hamamatsu has developed a jet-type water-cooled heat sink, called FUNRYU [2] with a less complex structure than the MCC but with comparable thermal resistance. Since there is no micro-structure the possibility of blockage is reduced. However, the coolant is still in electrical contact with the electrically-active laser diode, and the CTE mismatch is still present.

To avoid these problems the use of low temperature co-fired ceramic (LTCC) has been considered as a substitute material for the fabrication of coolers for high power diode lasers. Feeler *et al.* [3] report the fabrication of the first LTCC water cooler for MCC and jet impingement coolers. High-power laser diode bars and stacks have been reported using these LTCC devices. [4].

In this paper, our objective is to extend the LTCC cooler concept to the single BA emitter type of

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diode laser, which currently emit up to 12 W per device. Normally, single devices are conduction cooled to an external heat sink. However, the future trend is towards use of multiple chips within one package, where active water cooling is desirable. A laminated LTCC substrate seems a promising approach to both distribute water to individual chip coolers, and provide a stable platform for the addition of optical components for beam combining and fiber launch.

LTCC technology is well-established for high-performance low-volume applications, such as those in military and space applications, and high-volume cost-sensitive applications, such as those in the automotive and portable wireless industries, due to its numerous material advantages. Recently, there has been much interest in the use of LTCC as a platform for optical integration of both active and passive components [5]. The feasibility of easily machining detailed structures in single layers to form very complex 3D structures make LTCC attractive platform for optical integration.

LTCC tapes are often formed mechanically by drilling, punching or stamping methods. Ceramic foils are typically machined in their green, pre-fired, state. However, mechanical methods are limited in hole diameter and the density of features. Mechanical machining is also subjected to wear due to tool/work piece physical contact. To avoid these problems we have previously developed a micro-machining CO₂ laser technique for LTCC, in green state, with high speed and high resolution capabilities, used for this study.

2. MICROMACHINING TECHNIQUE

Laser machining of LTCC has replaced some of the mechanical methods. In 1999, Imen and Allen reported the use of a high peak power TEA CO₂ laser to machine green alumina sheets, but found air breakdown over the ablation site and plasma screening [6]. They avoided these problems by working at reduced pressure. Solid-state Nd:YAG lasers at 1.06 μm have been used for drilling 75 μm to 500 μm diameter holes in green ceramic [7, 8, 9] with a reasonable quality. However, the material removal rate and overall machining control are too low for industrial processes due to relatively weak absorption of green tape at this wavelength. Diode laser machining of polymer/ceramic was reported in 2000 [10], again with poor performance due to a low absorption at 852 nm.

To overcome these problems, we have developed a novel “cold” self-cleaning technique for processing LTCC in “green” state [11]. This technique employs a low-power CO₂ laser, which

results in high speed with negligible thermal effects at the interaction site. This is a three stage “cold” process characterised by:

1. Absorption at 10.6 μm laser wavelength localised in the ceramic grains.
2. Rapid but controllable polymer pyrolysis at 200-400°C.
3. Transport of un-sintered ceramic particles from the site by polymer decomposition gases.

The CO₂ micro-machining laser has active power stabilization with power variations less than 1%. An acousto-optic modulator (AOM) controls the power on the green tape, providing individual pulses for via drilling and power control for continuous cutting or grey-scale micromachining. Typically, the power on target is few Watts for continuous cutting. The cutting resolution is approximately 50 μm .

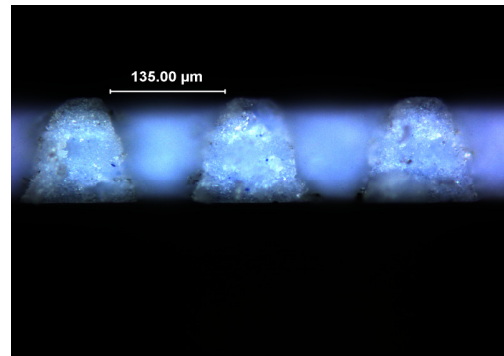


Fig. 1 Cross section of tape drilling with two pulses and fluence of 115 J/cm²

The quality of multiple shot drilling into one LTCC layer can be observed by the cross-section in Fig.1, illustrating the conical shape produced by two superimposed laser shots each with a fluence of 115 J/cm². The in-focus region indicates un-cut LTCC and out-of-focus are removed sections. The taper induced by the laser drilling is approximately 15°.

3. FABRICATION OF INTERNAL STRUCTURES IN LTCC SUBSTRATES

For the fabrication of our test water jet cooling device, Heraeus 130 μm thick HL2000 tape was chosen due to its zero shrinkage property in the X-Y direction. It shrinks uniformly by approximately 20% in the Z direction during sintering process. An initial design was made using 24 layers. Each layer was cut using the CO₂ laser micromachining technique outlined in Sec 2, forming, when stacked, a 3D structure with a number of holes, water

channels and inter-level water connectors. The 24 layers were laminated using a hot isostatic press at 10 MPa for 10 minutes at 70°C. In our first trial, the fired substrate suffered deformation due to sagging of the internal cavities and de-lamination of few layers. An example of a collapsed channel, after firing process, is shown in Fig. 2; the height of the channel was reduced from the expected 0.350 mm to 0.150 mm. This is a particular problem with isostatic lamination pressing.

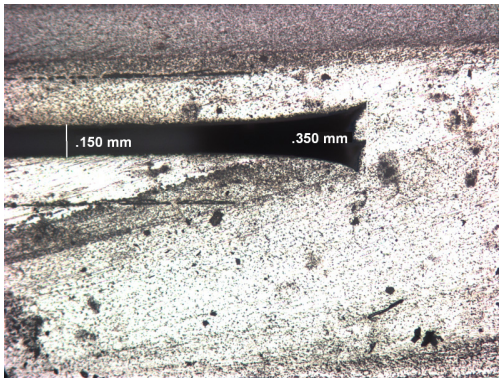


Fig. 2. Example of water channel collapse caused by unsupported isostatic lamination

To prevent the deformation of internal structures, sacrificial volume materials (SVM) were used to provide a mechanical support during the lamination process. However this must be successfully removed during the firing process. Nanocarbon tapes with a thickness of 250 μm from Thick Film Technologies were chosen.

To obtain a well defined inner structure a good fit between the LTCC apertures and the SVM fillers was needed. Nanocarbon tapes could be machined by a number of methods including traditional mechanical methods or by laser machining. To avoid the use of an extra tool, we have investigated cutting of the carbon sheets using our CO₂ laser system. We find that the mechanism for machining the nanocarbon tapes is very similar to the one for green LTCC. Fig.3 and 4 compare the depth of machining in nanocarbon sheets and green LTCC, respectively, versus the laser irradiance for different pulse durations of the AOM. The machining was done in raster mode at speed of 10 mm/sec, raster steps of 40 μm and a beam diameter of 100 μm ($1/e^2$). A similar threshold was observed for both materials, approximately 28 kW/cm² but the material removal rate for carbon is ~70% of that for LTCC tape. In multiple pass continuous cutting, the laser beam produces a taper of 17° in LTCC and 12° taper in nanocarbon. If same size cutting tracks are used

for both pieces, consideration of both the taper and cut offsets results in a gap between the LTCC and nanocarbon tape is approximately 110 μm when there is no compensation. Figure 5 shows this to be an adequate fit between a nanocarbon disk and LTCC substrate, for both pieces with a designed cutting diameter of 3 mm. The 130 μm LTCC was cut by two passes at 10 mm/s, 200Hz pulse rate, with peak fluence of 28J/cm² and the 250 μm nanocarbon was cut by two passes at 5 mm/s, 400Hz pulse rate with a fluence of 65 J/cm².

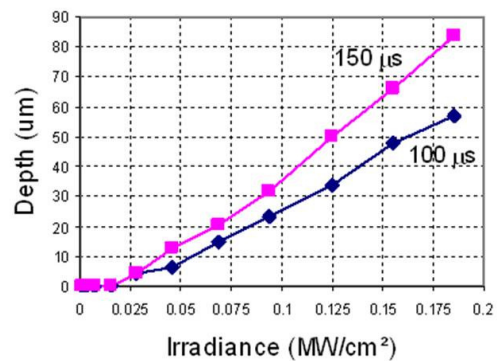


Fig. 3. Machining depth in nanocarbon sheet for different pulse durations

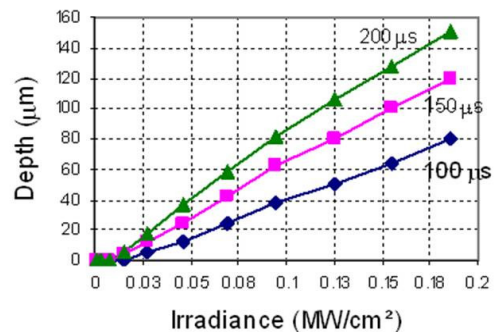


Fig. 4. Machining depth in LTCC sheet for different pulse durations

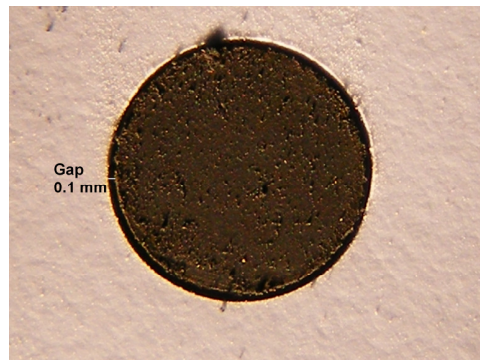


Fig. 5. Fitting between LTCC and nanocarbon piece without size compensation

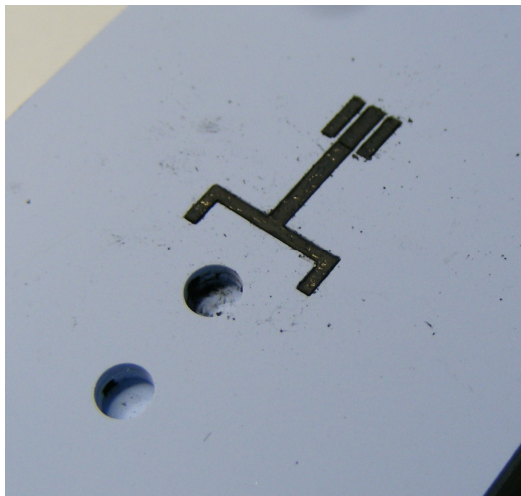


Fig. 6. Water channel filled with nanocarbon

Figure 6 shows an internal water channel layer photographed during stacking of unfired LTCC, filled with matching nanocarbon pieces. The final structure, after being filled, was laminated at 10 MPa for 10 minutes at 70°C.

Initial sintering trials used a firing profile which combined the two firing profiles recommended by Heraeus and Thick Film Technologies. However, we found that the structure showed deformation of the top and bottom surfaces due to damage by delamination and some broken layers in the sections below and above the nanocarbon-filled cavities. This can be observed after sectioning in the micrograph in Fig 7.

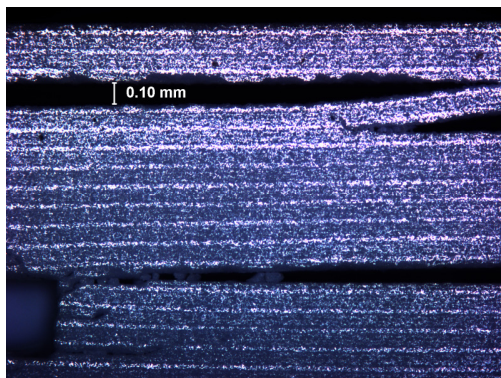


Fig. 7. Deformation of layers during firing process

We believe that deformation and delamination of layers results from internal gas pressurization during firing. In two stages during the firing process, gases are generated by nanocarbon filler. At 350°C the binder of the nanocarbon decomposes and subsequently, starting at 600°C the

remaining carbon sublimates creating gases. Due to the large amount of nanocarbon needed for water channel structures and the fast firing rate used in our initial samples, some of the gases remained trapped in the structure when LTCC layers began the sintering process. Apparently, this does not escape during the porous state of the LTCC tapes during the early stages of sintering.

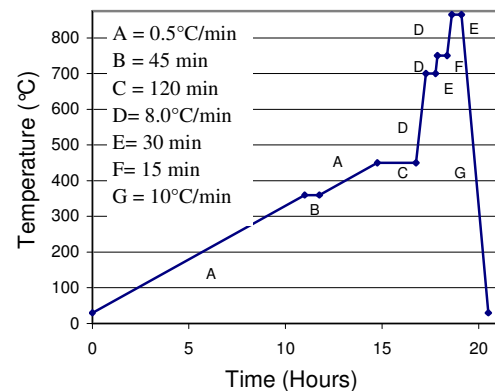


Fig. 8. Modified firing profile for LTCC filled with nanocarbon

Our solution at present is to extend the total period for sintering from the recommended ~4 hour cycle for the LTCC tape only, to allow more time for escape of the gas. Figure 8 shows our extended firing profile, of 20 hour duration which avoids the distortion of the carbon filled structure.

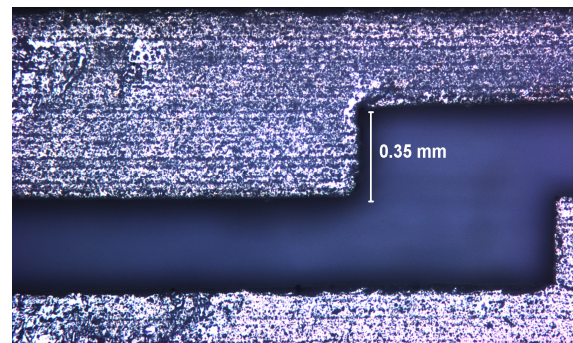


Fig. 9. Cross section buried water channel and via

Figure 9 shows an embedded water channel in a successfully sintered sample. The cross-section is a water interconnection, without delamination or cracking above or below the buried cavities.

4. FABRICATION OF SUB-MILLIMETER WATER JETS IN LTCC SUBSTRATES

Recently Barlow et al. reported the formation of jets and internal water channel structures in LTCC by automated mechanical punching for a similar application [4]. A number of different punches were used according to the sizes of localized feature and to refine edge quality to manufacture impingement water jets for a high-power laser diode bar. Accuracies and jet diameters were of the order of 25 μm and 200 μm respectively.

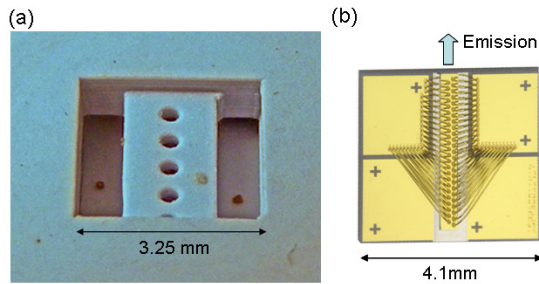


Figure 10 (a) View of Water jet, (b) Matching diode laser on AlN substrate

Figure 10(a) shows the finished prototype for our cooler structure, compared with a matching Bookham single emitter BA diode laser on its 400 μm thick metallised AlN submount. The initial attachment of the diode submount is to be by adhesive bonding for cooling tests, while in future, the LTCC surface can be metallized for solder attachment. The five water jet holes ($\sim 350\mu\text{m}$ diameter) and the surrounding water return cavity are visible. The two 800 μm x 400 μm water return channels and the laminations can also be seen. The distance between the jet exit and impingement on the AlN submount is 420 μm . The jet layout is designed to intensively cool the AlN directly underneath 3.6mm x 0.4mm heat generation area of the diode laser in Fig. 10(b).

We have investigated of the formation of jet holes through a total of four laminations, using only laser cutting and the standard lamination techniques. The series of 350 μm diameter contributions to the jet were cut in green LTCC using a trepanning cutting approach to accurately control shape. Figure 11 shows the green-state entry and exit sides of a single layer of a laser-machined jet. The typical pre-firing wall roughness was also shown to be a few tens of microns.

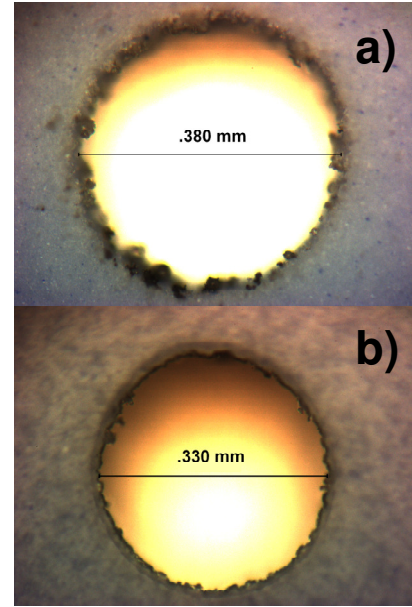


Fig. 11. a) Entry of a laser machined jet, b) exit side of jet

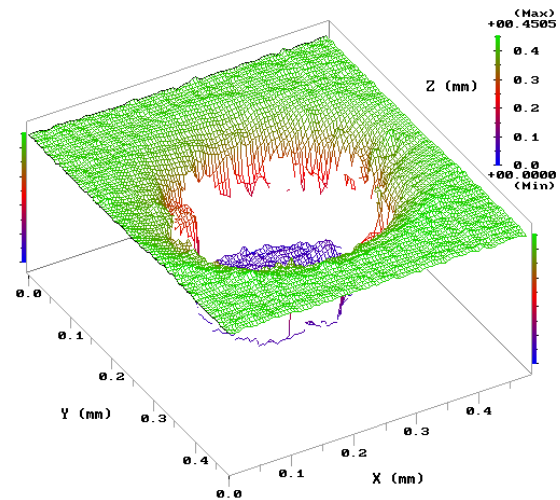


Fig.12. Top surface of a 4 layers jet

Figure 12 and Figure 13 show the surface profile of the topmost and bottommost LTCC layers (respectively) of the four layers jet. Nanocarbon filled the water gallery below the jet structures. The surface profiles were measured optically using a Scantron profiler with submicron-depth resolution. No deformation or misalignment of the jet was apparent after the lamination process from the experimental data shown in Figure 12 and Figure 13.

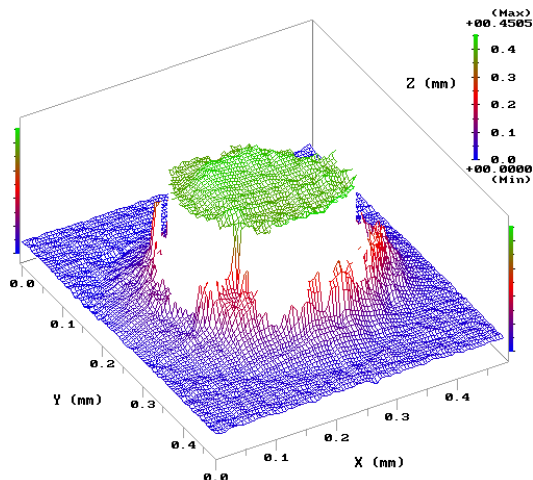


Fig.13. Bottom surface of a 4 layers jet

After the lamination and sintering process, without carbon filling in the jets, the typical wall roughness reduces to less than 20 μm . It is unclear whether the irregular internal surfaces of the water jet coolers affect the cooling performance by manipulating the turbulence within the jets.

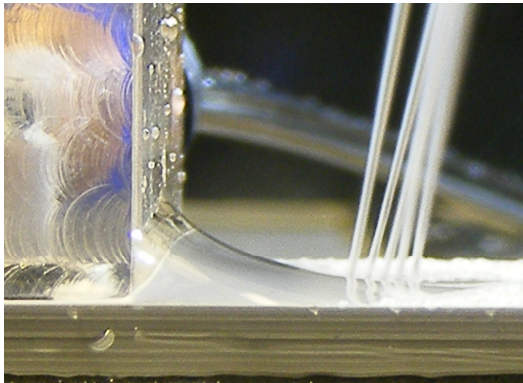


Fig.14. Water jet outputs

A photograph of the jets in action without the sealing aluminium nitride heat spreader is pictured in Fig. 14. A Perspex manifold is shown on the left. Five uniform jets of water towards the right of the image. Excess water from splash back is also shown on the LTCC substrate at the bottom of the photograph.

Using a temporary cover on the aperture in Fig 10(a), we measured water flow per jet of 0.03 L/min for a measured water pressure of 1.65 bar across the cooler. Based on calculations these results give a jet water velocity of 4.4 m/s and the Reynolds number of approximately 1611.

The efficiency of the cooler, along with the thermal impedance will be measured by monitoring

the associated wavelength dependency with temperature of the mounted laser diode.

5. CONCLUSIONS AND FUTURE WORK

In this work we have shown that high-quality 2D structures in LTCC and nanocarbon can be machined using a CO_2 laser micromachining process. By stacking these 2D layers, a complex 3D structure with a number of holes and embedded interconnecting water channels were formed. A modified firing profile avoids the internal deformation of the LTCC substrates associated with trapped carbon monoxide and dioxide gases.

The conical cut shape produced by laser machining is reduced during the firing process leaving a smooth surface finish. Well-defined water jets have been formed by stacking laser trepanned layers. Good jet alignment and no deformation are obtained without the need of SVM during the lamination and firing processes.

Our future work will include the study of cooling performance in function of the jet wall roughness and metallization of the top surface to allow the soldering of laser diodes on LTCC substrates. As well, the fabrication of LTCC coolers which allows the mounting of multiple single-emitter laser diodes and optical components (i.e mirrors, lenses and fibers) on the same LTCC substrate.

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