High Speed Cutting of Copper Foil with a 532nm Diode Pumped Solid State Laser for Microelectronics Applications

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Abstract

Copper is one of the most widely used materials in the microelectronics industry. As trends progress towards compact devices and miniaturisation in this sector the use of thin copper foils is increasing. Such foils are difficult to cut by conventional means, and so laser cutting is investigated as an alternative. Copper is highly reflective at longer wavelengths and so 532nm is identified as an industrial laser choice. The researchers investigate the use of 532nm, Q-switched, nanosecond pulse, kilohertz repetition rate sources for cutting Copper foils of varying thickness. The effects of pulse duration, M2 and repetition rate are studied empirically.

Keywords: Copper Cutting, Copper Foil, PCB, Flexible PCB, Laser Cutting, Nanosecond (ns), DPSSL, Diode Pumped Solid State Laser, 532nm, Green, Copper Vapour Laser Emulator

1 Introduction

The use of lasers for materials processing in the microelectronics industry is widespread and enabling for a wide variety of materials and applications. Most notable would be the use of Ultraviolet (UV) Excimer lasers in the manufacturing of Silicon (Si) chips to achieve ever-smaller feature sizes employing lithographic techniques. However there are many other significant uses of lasers in this field; notably resistor trimming, precision marking, via drilling for Printed Circuit Boards (PCBs), dicing wafers and micro joining techniques over a whole range of materials and employing a wide variety of lasers [1].

A material of great significance in the microelectronics industry is that of Copper (Cu) the ubiquitous conductive material used for interconnects in almost all electronic devices in both pure form and as laminates. This material poses challenges to process conventionally being soft and prone to deformation and delamination when using contact processes such as punching or drilling. It is also a challenging material to process using lasers as it exhibits high reflectivity at longer wavelengths, see figure 1 below, and has an extremely high thermal conductivity 385 W/mK (at 293K) [2].

The high reflectivity makes it difficult to process Cu with longer wavelength lasers such as CO_2 at 10.6µm and Nd:YAG at 1.06µm although with care limited successful processing has been reported of Cu and it’s alloys [2,3]. This is only possible due to increasing absorption caused by developing melt and changing surface topography during cutting and drilling. High reflectivity however reduces the potential for efficient energy transfer from the laser to the substrate at such wavelengths. This is compounded by the high thermal conductivity rapidly dissipating heat from the interaction zone.

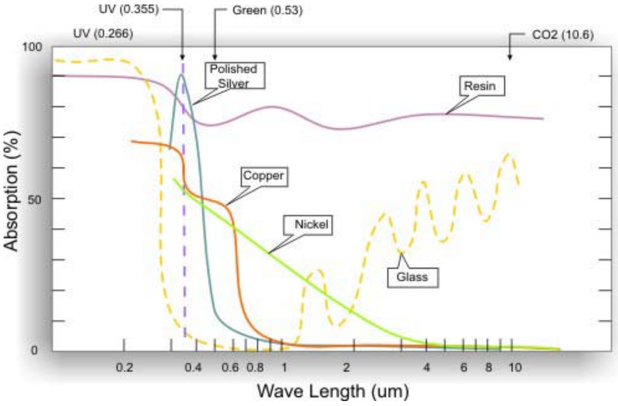

Fig. 1: Material absorption as a function of wavelength [4]

An alternative strategy would be to employ shorter wavelength lasers – either harmonics of Nd:YAG or

Excimer which will enjoy greater absorption promoting more efficient energy transfer, see table 1.

Tab. 1 Material reflectivity of copper at fundamental and Nd:YAG harmonic wavelengths [5]

Wavelength (nm)	1064	532	355
Cu Reflectivity (%)	97	61	42

An additional benefit of going to shorter wavelength is that the optical penetration depth is minimised, localising energy input to a smaller volume and reducing the potential for heat transfer. This is especially relevant in the cases where cutting is required close to embedded heat sensitive components. This is described in the following well-known equation:

$$W = \frac{\lambda}{4\pi k} \qquad (1)$$

Where W = penetration depth, λ = laser wavelength and k = extinction coefficient [6].

Excimer and Q-switched Nd: YAG lasers and their harmonics also feature nanosecond (ns) pulse durations, which also serve to reduce the thermal conduction into the substrate, described in the following familiar equation:

$$D = (4\kappa t)^{1/2} \qquad (2)$$

Where D = thermal penetration depth, κ = thermal diffusivity of the material, and t = pulse duration [6].

The classic widely adopted industrial application for laser Cu processing is in via drilling of PCBs. In this case the task is to drill blind or through vias to allow dense circuit wiring; specifically to precisely drill through a lamina Cu-Insulator-Cu substrate. In some cases a short wavelength laser is used to process the top Cu layer e.g. 248nm KrF Excimer and a longer wavelength laser e.g. 10.6µm CO_2 to selectively drill the insulating layer e.g. FR4. These techniques can achieve sub-100µm diameter vias but even further miniaturisation is being explored by employing 355nm lasers [7,8,9].

In this paper the authors are concerned with cutting Cu foils $\leq$ 400µm thickness with 532nm visible 2nd harmonic Q-switched diode pumped solid state (DPSSL) Nd:YAG lasers. The choice of laser type is due to practical industrial availability. 355nm lasers offer a slightly higher absorption, however reaching the 3rd harmonic is more costly in power loss and the most powerful commercially available 355nm lasers are in the order of 10W. In addition studies by Tunna, O'Neill et al [10] suggest that 532nm processing may actually be more efficient than 355nm due to localised increased recoil pressure from plasma removing melt more efficiently.

Excimer lasers offer 100s Watts at UV wavelengths but require mask imaging, employ dangerous gases and have lifetime issues so are not favoured by industry. So commercially available 532nm lasers at >20W low M^2 and >90W high M^2 are the tools chosen.

There is precedent for successful high quality laser processing of copper, employing visible wavelength, ns pulse duration, kHz repetition rate lasers. This comes from Cu: Vapour lasers emitting 25-50ns pulses at 511,578nm [11]. This type of laser has been available for over 25 years. However Cu: Vapour lasers have a poor reputation for reliability in industry and so a more rugged diode pumped solid-state 532nm laser, 'a Cu: Vapour laser emulator' is an attractive industrial choice for this application.

2 Experimental

In all cases pure copper foil, 200µm and 400µm thick, is used for cutting test samples. Grooves are cut into the foil samples with the laser to assess the depth of cut and cut characteristics. Sample thickness is determined by maximum achieved groove depth in testing. The cut samples are sectioned, cold mounted, polished and etched.

Measurements are made using a Nikon LM1500 optical microscope with a PC interface via a 12 Mega pixel camera into Lucia G software. This software allowed microscopic measurements to be made against a Nikon standard. Depth measurements were made using a Mitutoyo dial gauge.

In all cases the beam is collimated from the laser using a Galilean telescope and scanned over the workpiece using a Scanlab HurryScan 14 532nm scanner. Flat field lenses were employed for both lasers used. A 56mm f.l. lens is used for the Starlase AO2G, achieving a theoretical spot size of 86µm ($1/e^2$). A 160mm f.l. lens is used for the Starlase AO1G, achieving a theoretical spot size of 32µm ($1/e^2$).

Two 532nm Q-switched diode pumped solid state lasers were employed and compared for testing. A higher power, high M^2 laser, a Starlase AO2G with a maximum power output of 100W; and a lower power, low M^2 laser, a Starlase AO1G with a maximum power output of $\geq$ 20W. The key characteristics of each laser are show in figures 2 & 3 below:

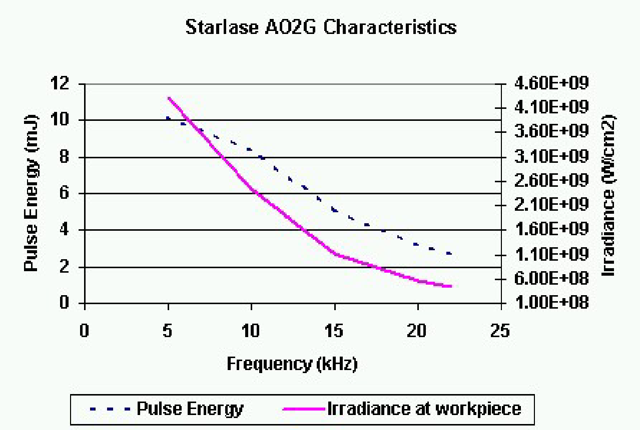

Fig. 2: Starlase AO2G Characteristics

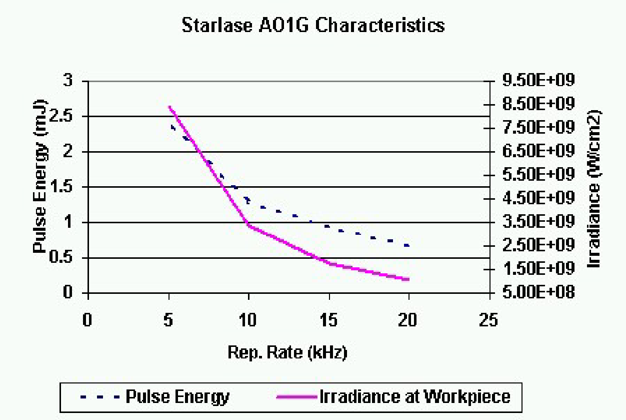

Fig. 3: Starlase AO1G Characteristics

The Starlase range of lasers is manufactured exclusively by Powerlase Ltd, UK.

3 Results and Discussion

In order to assess the potential cut speed and corresponding material thickness possible, a sequence of grooves were cut into copper foil. The thickness of the foil was chosen to be greater than could be cut in practice to allow quantitative assessment of kerf structure. Optimal cut performance; material thickness and kerf evolution could then be analysed with regard to available laser parameters.

Customer interest prompted the use of two 532nm Q-switched DPSSL with differing laser characteristics. The Starlase AO2G is a high M^2 multi-mode 532nm laser capable of generating up to 100W output power, and with a rep. rate range of 4-22kHz. The Starlase AO1G is a low M^2 laser capable of generating up to 20W output power, and with a rep. rate range of 5-20kHz. Obviously the AO2G cannot be focussed to achieve such fine features or such high irradiance but offers significantly more pulse energy and corresponding average power than the AO1G, see figs 2 and 3. Part of this assessment is to determine which laser is most appropriate for cutting different Cu thicknesses.

In most cases, kerf depth is expressed by reference to exposure time. This approach allows direct comparison of multi-pass and single pass cutting strategies in terms of overall achievable cut speed and depth. By knowing the length of the groove, the achieved kerf depth and exposure time it is possible to determine effective cut speed.

In this study, the effect of differing frequencies (rep. rates), pulse overlap and focal position will be examined. Finally a comparison of cutting between the two lasers will be undertaken based on these results.

3.1 Frequency

For both the AO2G and AO1G tests of exposure time versus available repetition rate were conducted – to determine the optimal regime for cutting. In all cases pulse overlap was set to 0%, each pulse being adjacent but not overlapping, in order to minimise plasma effects. Figures 4 and 5 below show the results:

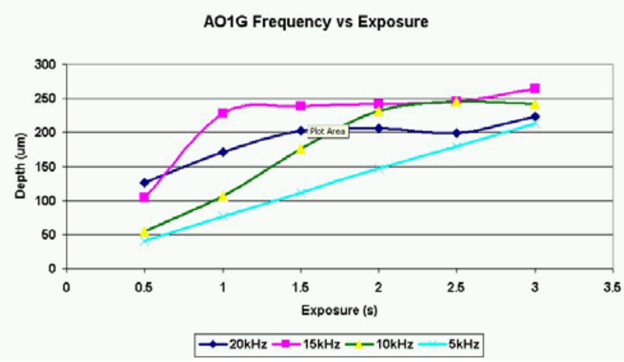

Fig. 4: Frequency (Rep. Rate) vs. Exposure for AO1G (low M^2)

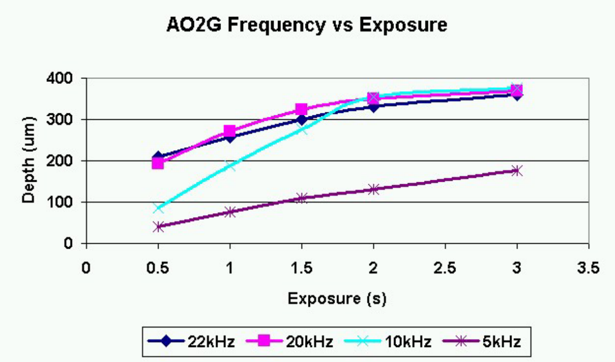

Fig. 5: Frequency (Rep. Rate) vs. Exposure for AO2G (high M^2)

A number of clear correlations emerge. As expected kerf depth increases with time – however the general trend for both lasers is that the material removal rate (MRR) decreases with increasing exposure. This appears to follow a logarithmic function – tending to zero with increasing exposure. This phenomena has been reported previously in the literature, Mayerhofer et al observe this trend for a range of metals whilst drilling with a Cu: Vapour laser [11]. This trend indicates that cutting thin foils will be very rapid, but that the process becomes self-limiting for thicker sections, and that cutting thick copper may not be suitable for such lasers.

The reason for this self-limiting behaviour may suggest itself from the differences in kerf erosion with frequency. For both laser types, higher frequencies tend towards their upper limit before the lower frequencies do. It is suggestive therefore that high frequency processing is likely to be most efficient for thinner foils. The results also may potentially point to high irradiance low frequency cutting allowing deeper cuts.

This suggests that the limiting factor in achievable kerf depth is irradiance – the higher the irradiance for a given laser, the greater the attainable kerf depth. The authors suggest that this indicates that the Cu cutting process is ablation threshold dependent. As a kerf erodes, the area over which each subsequent laser pulse is spread increases, reducing the irradiance at that point until it drops below ablation threshold; resulting in a maximum achievable depth for a given irradiance and ultimately a self-limiting process. The effect of wave guiding can be reasonably discounted due to the high absorption of Cu at 532nm (see table 1).

It must be noted however that high frequency processing is more efficient for thin Cu foils – more quickly reaching its maximum depth. This may be attributed to the fact that a high irradiance will result in a greater proportion of material removed entering a vapour phase – a less efficient MR mechanism than lower energy melt removal – and will also be more prone to plasma formation dissipating incident laser energy. This is supported by the increase in kerf width with lower frequency in the same experiment, see figure 6 below:

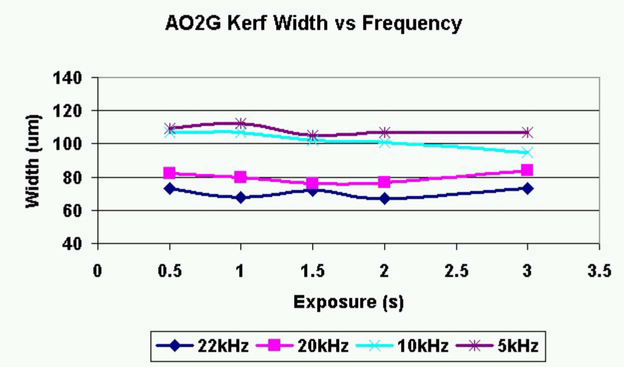

Fig. 6: Kerf Width vs. Frequency for AO2G (high M^2)

As can be seen, the entrance kerf width is fairly constant with exposure, but markedly larger at lower frequencies with corresponding higher irradiances.

This irradiance-based effect gives the laser user the ability to control the processing parameters to suit the substrate in question. For thin foils <100µm high frequency processing will offer faster cut speed, but for thicker foils the user can achieve cuts with lower frequency processing but at the expense of speed.

This self-limiting effect can be seen in the following micrographs.

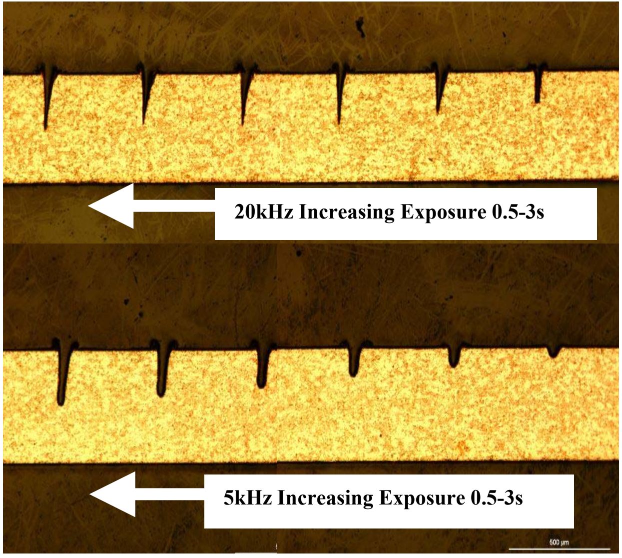

Fig. 7: Kerf Geometry with Exposure for AO1G (low M^2)

The 20kHz processing quickly reaches a maximum depth, whilst the 5kHz removes material slower but appears to have not yet reached its upper limit even after 3s; its MRR appearing constant.

Figure 7 shows markedly different kerf geometries, 20kHz processing resulting in a steep 'V-shaped' kerf whilst 5kHz achieves a more 'U-shaped' kerf. This can be seen more clearly in figure 8 below:

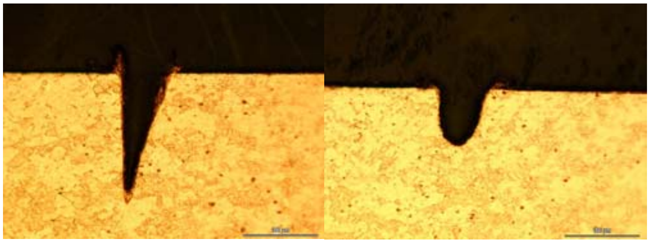

Fig. 8: Kerf geometry after 1s exposure time 20 & 5kHz

Korner and Mayerhofer et al describe this effect from drilling with Cu: Vapour lasers observing different material removal mechanisms with irradiance. They attribute the 'V-shaped' kerf to 'Ablation by stationary evaporation' and the more 'U-shaped' kerf to 'Ablation by stationary melt displacement and ejection' a higher irradiance process [12].

Both Korner and Mayerhofer et al and Tunna, O'Neill et al describe in drilling copper with visible laser radiation that drilling efficiency increases with irradiance [10,12]. However the data from this paper appears to refute this - most practical efficient cutting being achieved for thin foils at lower irradiance. On closer examination we see that in both cited examples a constant repetition rate is employed. Whereas in this empirical paper, a range of repetition rates are used; thus more efficient processing might well be seen at 5kHz on a pulse by pulse basis, however 20kHz has 4 times as many pulses, so even a less efficient MRR by pulse results in faster cutting.

A final observation is that figures 4 and 5 show that the AO2G can achieve a greater maximum cut depth ≈ 350µm than the AO1G ≈ 250µm. The AO1G offers higher irradiances, however the AO2G has significantly more pulse energy available. This may be attributed to more material being removed per pulse with a larger energy transfer albeit in a less efficient MR irradiance regime. Thus the AO2G is better for thicker section cutting – if larger spot size is acceptable.

3.2 Pulse Overlap

For thin section cutting high repetition rate processing is identified previously as most efficient. Consequently 20kHz, the highest available common rep. rate is used to assess the effect of pulse overlap. Pulse overlap is expressed in terms of a % of the spot size, 32µm ($1/e^2$) and 86µm ($1/e^2$) for the AO1G and AO2G respectively. Highest pulse overlap is achieved in single pass cutting; however as pulse overlap decreases the cutting regime becomes multi-pass. Figure 9 shows results from the AO1G.

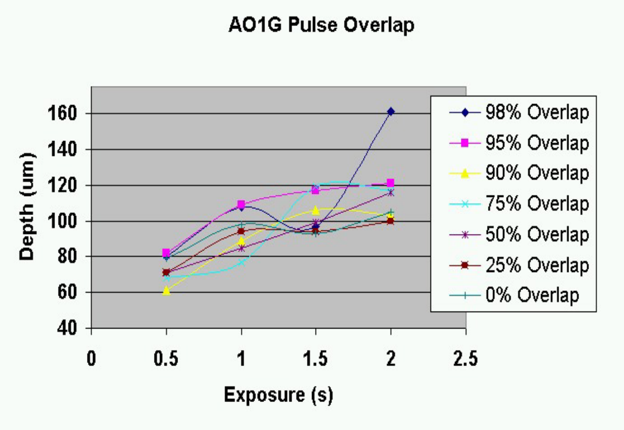

Fig. 9: Low M^2 AO1G Pulse Overlap at 20kHz

As in the previous section, we generally see a logarithmic tendency to limited removal with increased exposure. Interestingly the general trend is that of increased MRR with increased pulse overlap. This is in good agreement with the literature; Abedin, Coutts and Webb describe a similar effect for machining Cu with a 527nm Q-switched laser [13]. They attribute four possible mechanisms: localised heating of the substrate enabling more efficient MR with subsequent pulses, increased plasma coupling, elimination of oxidation layers by the first pulse and rapid change in surface morphology as the kerf erodes achieving more efficient energy coupling. The first three rely on localised heating of the surface enhanced by high pulse overlap compensating for the high thermal conductivity of the material. Although increased plasma coupling might result in increased kerf widths due to diverse heat transfer at high overlap – and the authors saw no evidence of this.

On close inspection an interesting phenomenon is that of the depth achieved by 98% overlap, 2-second exposure, nearly a third more than fits the prevailing trend, see figure 10.

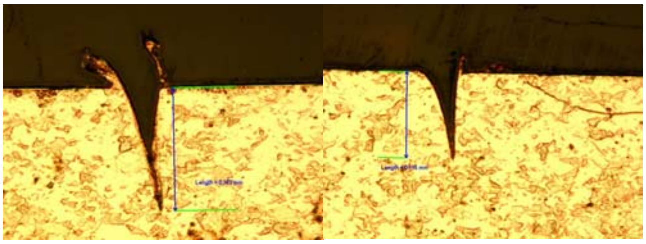

Fig. 10: 98% Overlap and 50% Overlap, 2s exposure AO1G

If we inspect comparative micrographs, we see that at 50% overlap a clear 'V-shaped' kerf is cut. However at 98% overlap such formation only passes down into half the depth of the kerf. The remainder of the kerf has penetrated, but shows poor material removal and is unlikely to have achieved a cut – appearing more like a laser weld. There is evidence of such behaviour in the literature. Li and Anderson report that when processing stainless steel and brass with a 532nm Q-switched laser and a high pulse overlap, the beam penetrates the material well before a cut is achieved [14]. They measure a penetrating laser power before the cut is achieved, but suggest that despite the laser creating an orifice in the material, the melt viscosity and surface tension prevents immediate material removal – analogous to laser keyhole welding [15]. Therefore this regime does not look likely to achieve good cutting results.

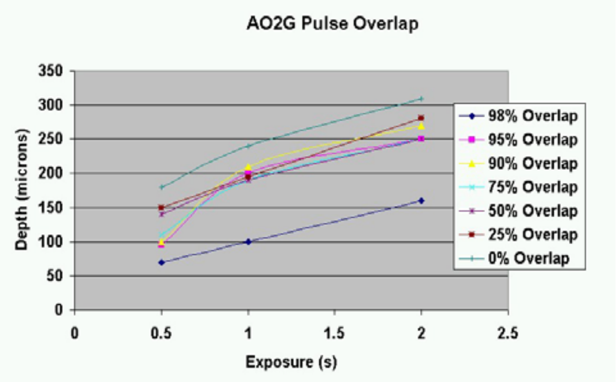

Fig. 11: High M^2 AO2G Pulse Overlap at 20kHz

The AO2G results are quite different see figure 11. The correlation is clearly reversed, low overlap leads to increased material removal. The authors speculate that the larger pulse energy over a larger kerf width may result in more localised heating resulting in excess plasma formation at a high overlap. However the cause is not clear.

3.3 Focal Position

The focal position of the laser may often be crucial in achieving optimal cutting. In this case to achieve the desired feature size, the high M^2 AO2 has a very short Rayleigh range 260µm vs. the low M^2 AO1G of 856µm. Therefore the AO2G is likely to be very sensitive to focal position.

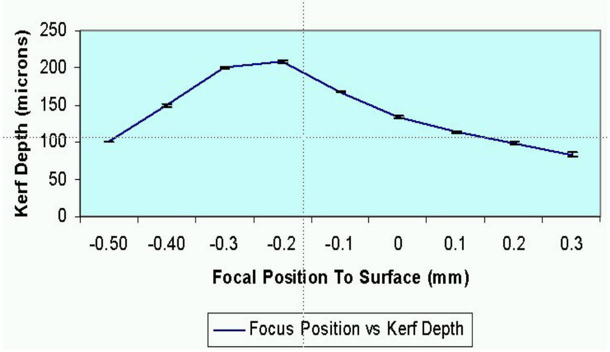

Fig. 12: Focal position effects for AO2G

Figure 12 above shows that the AO2G is extremely sensitive to focal position, a variation of 100µm resulting in a reduction in kerf depth of nearly 25%.

As can be seen in figure 13, the effects are significantly reduced for the AO1G, and improvements

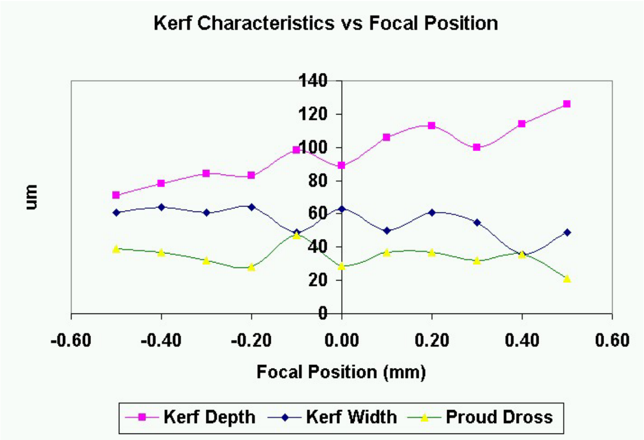

Fig. 13: Focal Position Effects for AO1G

in terms of kerf depth, and reduction in dross and kerf width achieving by focussing into or below the substrate. This may be due to the higher intensity focal waist achieving improved MRR at the base of the cut, and increasing recoil pressure at the base to cause more efficient melt ejection.

3.4 Comparison of Cutting by Laser Type

A comparison is made in terms of cutting with each type of laser. Customer targets are for thin film, so high frequency is optimal; 20kHz is employed for an exposure time of 1s. A comparison will be made in terms of volume removed/unit energy and cut depth achieved/unit energy. In each case the kerf will be assumed to be a symmetric isosceles triangle - close approximation to the 'V-shape' seen.

Tab. 2: Cut Comparison by Laser Type

Laser	**AO2G**	**AO1G**
M2	High	Low
Cut Depth (µm)	272	172
Kerf Width (µm)	80	50
Material Removed/Unit Power (μm^3/W)	0.002	0.003
Cut Depth/Unit Power (µm/W)	4.12	12.74

Table 2 clearly shows that the lower M2 AO1G offers much more efficient processing in terms of material removal but particularly in terms of possible cut depth.

4 Conclusion

It is determined that cutting Copper using a 532nm Q-switched DPSSL is possible. The process is determined to be self-limiting to a maximum thickness by falling irradiance within the kerf as it develops. This manifests a logarithmic decline in material removal with increased cutting time. High frequency cutting offers highest efficiency for cutting thin Cu. Thicker Cu may be cut using lower frequency higher irradiance processing – but at the expense of speed. In all cases there is an upper limit of substrate thickness that can be cut – this is in good agreement with the literature. Varying pulse overlap can be employed to improve cut rate for both laser types; and focal position is important in both cases, but particularly sensitive for the high M^2 laser due to the low depth of focus.

The low M^2 laser is demonstrated to be more efficient for cutting thin Cu foil than the high M^2 laser. However, the significantly higher pulse energy of the high M^2 laser makes it suitable for cutting material thicknesses >200µm.

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