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Processing benefits of high repetition rate and high average power 355 nm laser for micromachining of microelectronics packaging materials

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ABSTRACT

It has been shown that micromachining of polyimide using a mode-locked high repetition rate, 80 MHz, 355nm laser is more efficient than the q-switched laser at same wavelength and same power level in terms of material removal rate. In this study we have explored and characterized the benefits of using high repetition rate, high average power, 355 nm mode-locked and q-switched lasers for micromachining of various microelectronics packaging materials that have different thermal properties. The removal rate and quality of machining have been analyzed against the difference in thermal properties of the material. The implications of the results observed are also discussed from practical manufacturing perspective.

Keywords: laser, q-switched, mode-locked, micromachining, Microelectronics, 355 nm

1. INTRODUCTION

For more than a decade, Newport and its Spectra-Physics Lasers Division have supplied laser and photonic solutions to the Semiconductor industry. When the first mode-locked quasi-cw ultraviolet lasers were introduced in early 2000, they opened up a whole new regime of material processing that used a very low energy picoseconds pulse at a very high repetition rate. The picoseconds pulse duration allows clean and precise removal of material with a high peak power; high repetition rate allows processing at a speed that was never achieved by using a similar average power nanosecond pulse q-switched laser. Both of these features of mode-locked laser processing are very attractive to various laser applications in the semiconductor and microelectronics industries where more and more precision in processing of features and higher throughput rates are demanded. Also, high peak power and picoseconds pulse width allows processing of features with very minimal thermal damage.

In past experiments, it had been demonstrated clearly that a 355 nm mode-locked laser processes materials such as polyimide and FR4 resin at a much higher processing speed than a 355 nm q-switched laser when both lasers had the same average power. Whereas, for material such as silicon and copper it was observed that, at the same average power, a nanosecond q-switched laser was more efficient in material removal than the picoseconds mode-locked laser [1,2].

The current study was focused on further characterizing the advantages and disadvantages of both 355 nm mode-locked and q-switched lasers for processing of polyimide, silicon, and copper. In addition to exploring the limit of processing deepest feature in each material, we also explored a process parameter space that exploits the characteristics of each laser to achieve the best processing results from throughput and processing quality perspective.

1.1 General Laser Processing in Microelectronics Industry

In the Semiconductor and microelectronics packaging industry, manufacturers are always searching for ways to process smaller features at faster speeds. Today, there are different types of lasers that are used to achieve reduced sizes and higher throughput. Two of the most common solutions are Q-switched UV diode pumped solid-state (DPSS) lasers and mode-locked UV DPSS lasers.

1.1.1 Q-Switched Lasers

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A Q-switch is a device that creates high loss in the laser cavity which prevents lasing while the gain medium is being pumped. Pumping puts energy into the laser medium, and when this has built up to a maximum value, the Q-switch is set (opened) to enable lasing. Laser action begins almost instantaneously. Because of the high gain that has built up in the laser medium, laser output power rapidly rises to a very high value. However, the intensity of this pulse rapidly drains all the stored energy out of the gain medium, and the output decreases almost as quickly as it has risen. In fact, for many commercial lasers, the pulse duration corresponds to only a few trips around the laser cavity, with typical values of tens of nanoseconds or less.

1.1.2 Mode-locked Lasers

The shortest pulses and highest repetition rates, typically around 100 MHz, are obtained with a technique called mode-locking. Typical mode-locked pulse durations range from a few femtoseconds to a few picoseconds.

In practice, two things are necessary to achieve mode-locked performance with transform-limited pulses — a reliable mode-locking mechanism and some type of dispersion compensation. A laser is a free-running amplifier, and as such will naturally operate in a regime that produces the highest gain. The goal of all mode-locking mechanisms is to lower the gain in the CW regime with random phases relative to the gain in mode-locked operation. Mode-locking mechanisms can be either active or passive. In active mechanisms, cavity losses are modulated at the round-trip frequency, which inhibits CW operation while having no impact on the gain for the short pulse propagating through the cavity. In early lasers, this was accomplished by wobbling one of the cavity mirrors. More recently, active mode-locking is typically achieved using an acousto-optic modulator (AOM).

With the introduction of q-switched and mode-locked lasers, two different processing regimes have emerged. The mode-locked laser processing regime favors a picosecond pulsewidth, very high repetition rates (MHz), and very low energy per pulse (nJ/pulse). In comparison, the q-switched laser processing regime uses a nanosecond pulse width, low repetition rate (kHz), and high energy per pulse (μ J/pulse).

2. HISTORY

Some of the results of the past studies [1,2] comparing performance of a mode-locked laser against the q-switched laser for various materials are shown in Table 1.

Table 1. Results from previous studies - comparing mode-locked and q-switched lasers for materials processing.

Material	Thickness, μm	Maximum Cutting Speed, mm/s	
		Mode-locked laser 10 ps, 80 MHz	Q-switched laser 35 ns, 30 kHz
Polyimide	50.8	600	80
	127	45	25

Material	Silicon	
	Cutting Speed, mm/s	Maximum depth cut, μm
Mode-locked laser 10 ps, 80 MHz	100	12
Q-switched laser 12 ns, 50 kHz	150	26.2

Material	Copper	
	Cutting Speed, mm/s	Maximum depth cut, μm
Mode-locked laser 10 ps, 80 MHz	100	2
Q-switched laser 35 ns, 30 kHz	200	10

While data from this previous study shows which laser can provide better results at a specific material thickness, it does not provide more insight into what happens when there is an increase or decrease from that specified thickness. In addition, in that previous study while the average power for both lasers was same, peak power was different. This could impact processing results.

So in order to provide a better comparison of the two types of laser, the current study focused on differentiating mode-locked lasers versus the Q-switched lasers' processing capability, for the same average power and same peak power. Also, various scribe depths achieved by both lasers at various cutting speeds have been analyzed. The goal was to determine which laser performs better from material removal perspective for a given material and to determine the quality of the processed features.

3. EXPERIMENTAL SET UP

The two lasers used for this study were a mode-locked, quasi-cw Vanguard™ laser operating at 80 MHz with a 12 ps pulse width and a q-switched HIPPO™ laser operating at 80 kHz with a 12 ns pulse width. Both lasers were set to provide output at 355 nm wavelength. The experimental set-up, which is shown below in Fig. 1, included the laser, a beam expander, the scan head, and a sample stage.

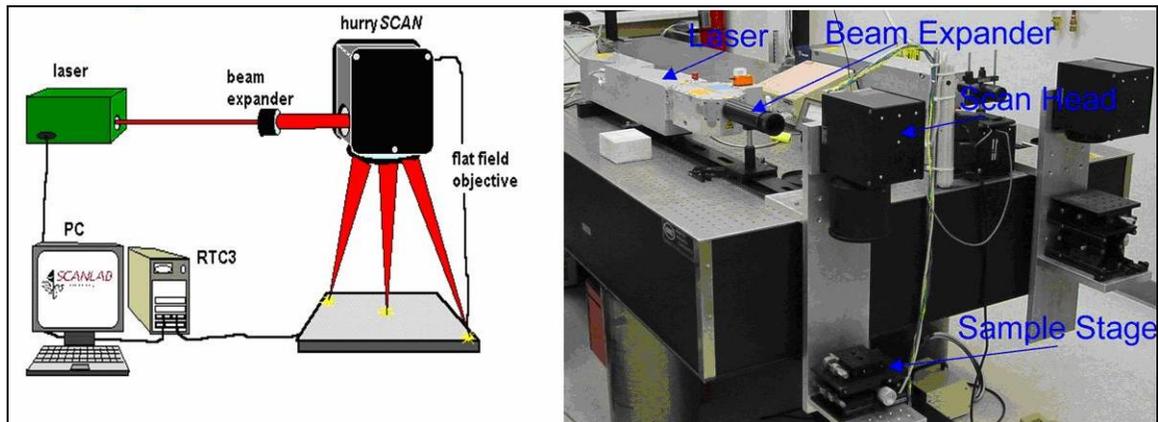


Fig. 1. The Experiment Set-up

3.1 The HIPPO Laser

The Spectra-Physics HIPPO series is an advanced diode-pumped solid state family of high power q-switched lasers specifically designed to produce high output powers combined with exceptionally short pulses. With pulse widths shorter than 15 ns in the IR and 11 ns in the UV, extremely high peak powers can be achieved making the HIPPO the ideal laser source for all micromachining applications.

The 1064 nm HIPPO laser head is available with standard doubling, tripling, and quadrupling harmonic modules for green and UV applications (532 nm, 355 nm and 266 nm). This modular design makes the HIPPO an excellent choice for micromachining of various materials. Fig. 2 shows the HIPPO laser family.

3.2 The Vanguard Laser

Spectra-Physics' Vanguard™ UV is an advanced diode-pumped solid state laser that has been specifically designed to produce ultra-low noise, quasi-CW ultraviolet output. It delivers exceptional TEM₀₀ mode quality, outstanding long-term stability, and long lifetime. This rugged laser uses cutting-edge mode-locking technology to deliver up to 4W of quasi-CW, UV output at 355 nm. With a pulse repetition rate of 80 MHz, the Vanguard offers a superior solid-state alternative to replace power hungry CW ion lasers in a number of applications. Fig. 3 shows the Vanguard laser designed to provide 2.5W average power at 355 nm.

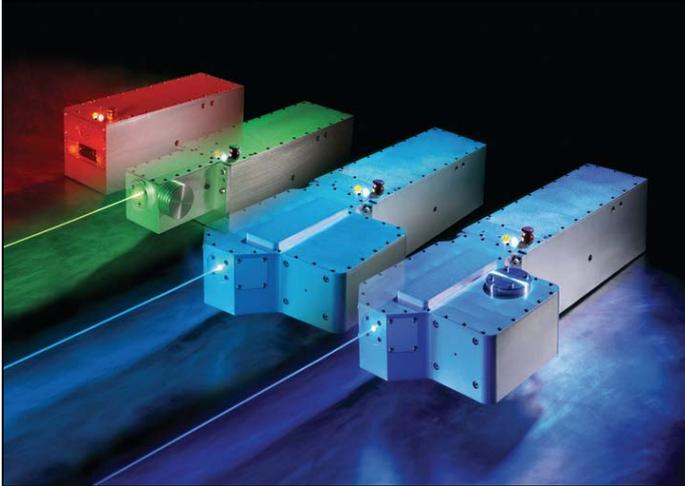


Fig. 2. The Spectra Physics HIPPO Lasers

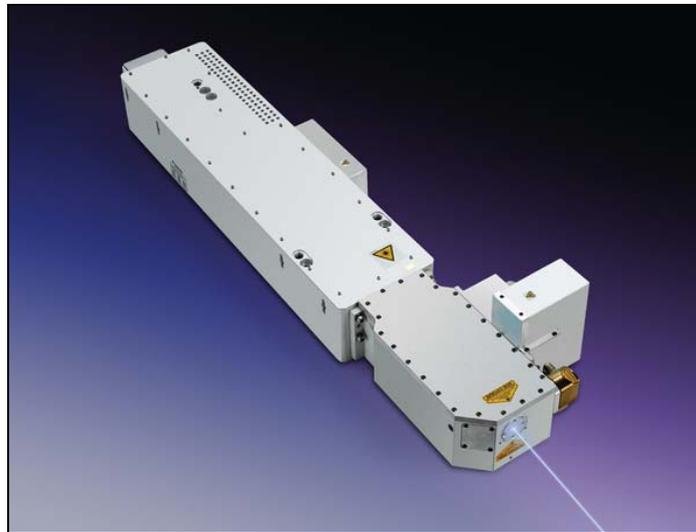


Fig. 3. The Spectra Physics 2.5W Vanguard Laser

3.3 Process Parameters

The Table 2 below shows the process parameters chosen for the experiment. The repetition rate for the HIPPO laser was chosen so that the peak power for both lasers remains the same. The average laser power for all the experiments in this study was also kept the same at 2.5W. The focused beam spot for various materials was changed to make sure we were scribing the material above the individual material's ablation threshold.

Table 2. Various process parameter conditions

	Polyimide		Silicon		Copper	
	Hippo	Vanguard	Hippo	Vanguard	Hippo	Vanguard
<i>Wavelength, nm</i>	355	355	355	355	355	355
<i>Rep. Rate, kHz</i>	80	80000	80	80000	80	80000
<i>Pulse Width, ns</i>	12	0.012	12	0.012	12	0.012
<i>Max. Power, W</i>	2.5	2.5	2.5	2.5	2.5	2.5
<i>Max. Peak Power, kW</i>	2.6	2.6	2.6	2.6	2.6	2.6
<i>Spot Size, μm</i>	10	10	8	8	4	4
<i>Fluence, J/cm^2</i>	40	0.040	62	0.062	249	0.249
<i>Intensity, GW/cm^2</i>	3.3	3.3	5.2	5.2	20.7	20.7

4. RESULTS AND DISCUSSION

4.1 Polyimide

Fig. 4 shows the difference in cut quality of a scribe done at same average speed of 400 mm/s between the HIPPO and Vanguard lasers. Besides few minor differences in edge quality both scribes look the same.

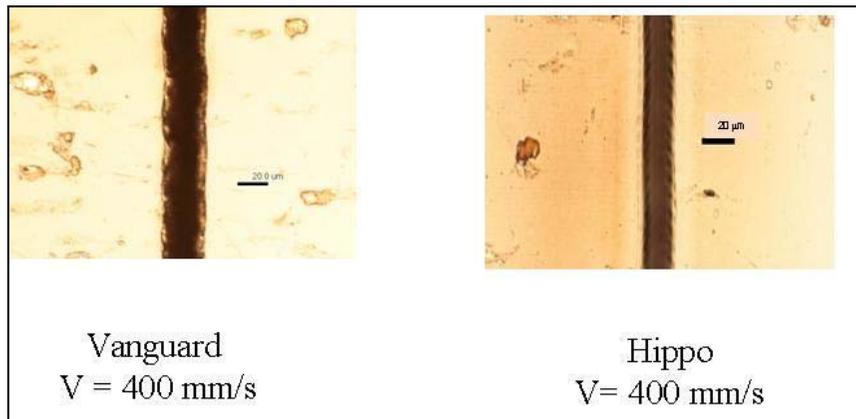


Fig. 4 - Comparing mode-locked Vs Q-switched cut quality in Polyimide

For polyimide film scribing experiments for the same average power of 2.5W at the sample surface various scribe depth achieved at a given cutting speed is shown in Fig. 5.

As observed in the previous study, results do indicate that for thinner films, 25 to 50 microns thick film, mode-locked laser is much better in material removal efficiency and it allows scribing of polyimide film at a much faster cutting speed. However the result also indicates that as the material thickness increases the “digging out” of material gets much more difficult for low energy picoseconds mode-locked laser pulses. As a result, the cutting speed for both laser becomes roughly equal for scribes that are about 80 microns deep. Also, to scribe material above 80 microns q-switched laser does a better job than the mode-locked laser. Therefore, the mode-locked laser does a better job of cutting thinner polyimide films, but for thicker films the q-switched laser provides better performance. Hence, for a given average power level there is a cross over point below which mode-locked laser is a better choice and above which the q-switched laser is a better choice for micromachining of polyimide film.

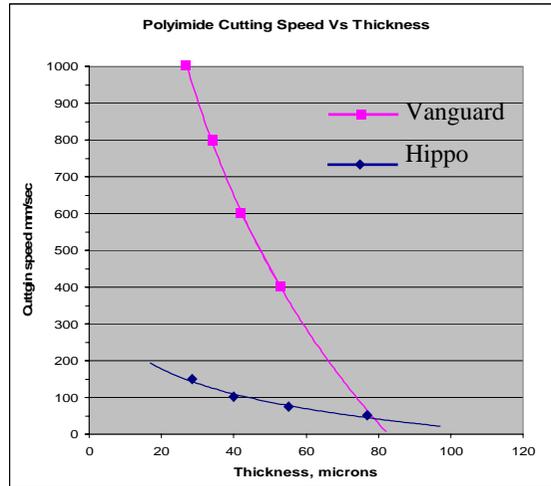


Fig. 5. Polyimide machining comparing scribe depth achieved at a given cutting speed

Fig. 6 below shows the scribe depth achieved for polyimide at various average powers at a cutting speed of 400 mm/sec. The data clearly shows that as average power increases mode-locked laser is able to cut deeper than a q-switched laser. In other words, at 1.0W average power mode-locked laser can cut 23 microns deeper than q-switched laser but at 2.5W it can cut 40 microns deeper at same cutting speed of 400 mm/sec. So a mode-locked laser with average power of 8 to 10W can easily cut through more than 100 microns film, q-switched laser at same average power will only be able to cut about 30 microns thick film at speed of 400 mm/sec.

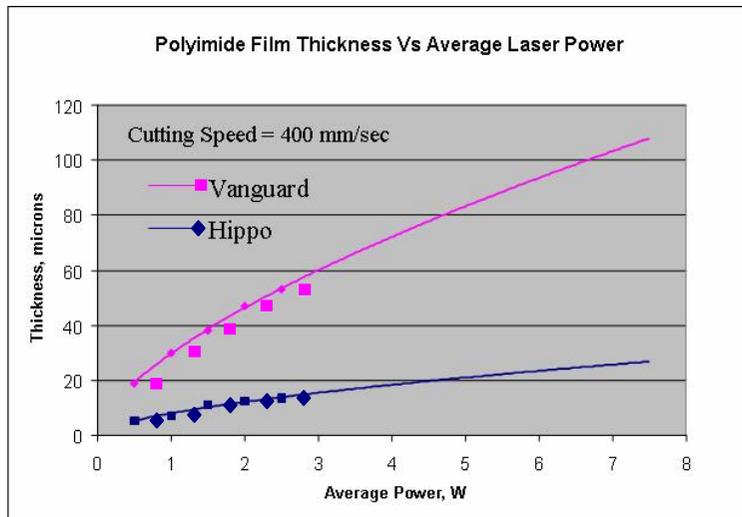


Fig. 6. Cutting depth for polyimide at different average powers

4.2 Silicon

For Si machining first thing that was observed was that for a given laser parameters, removing material in multiple pass at a higher scribing speed, rather than in an equivalent single pass scribing speed was providing cleaner removal of material. Fig. 7. shows the difference in scribes created using a Hippo laser for the same average speed for a different number of scans.

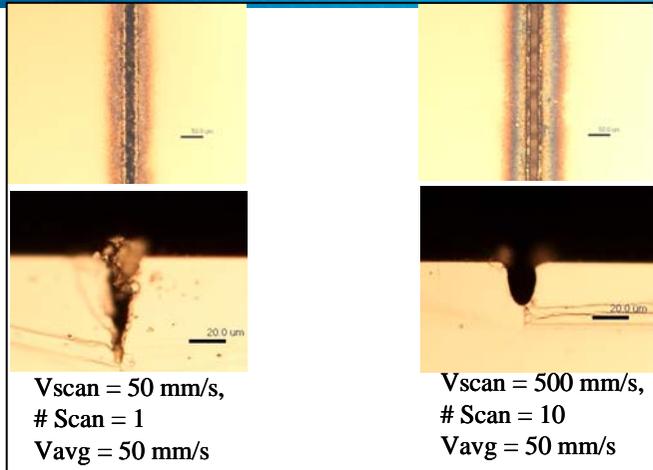


Fig. 7. Silicon machining using a q-switched HIPPO laser at same average speed using single and multiple scans.

The same effect of cleaner removal by multiple scans was observed for Vanguard laser also as shown in Fig. 8.

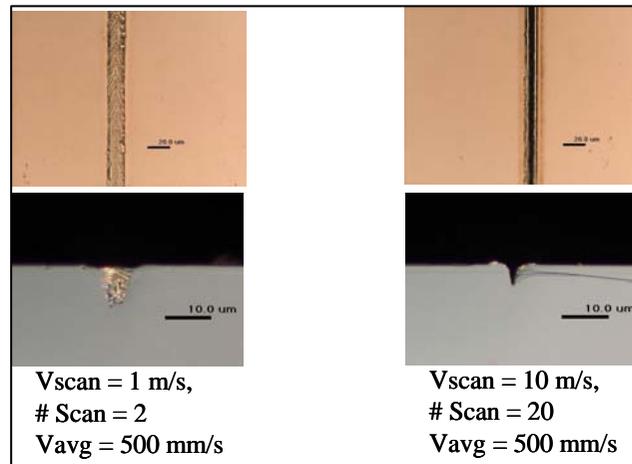


Fig. 8. Silicon machining using a mode locked Vanguard laser at same average speed using single and multiple scans.

Fig. 9 below shows the difference in cut quality of scribes created using the HIPPO and Vanguard lasers at same average speed of 500 mm/s and same average power of 2.5W.

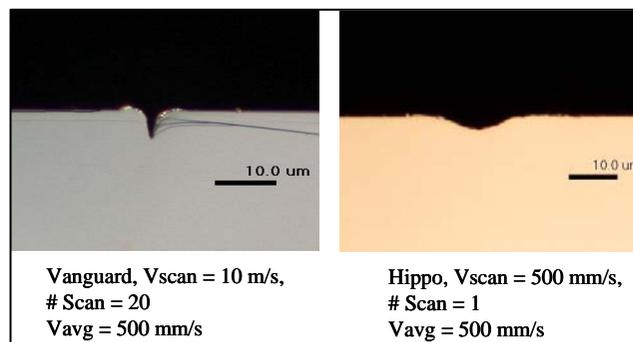


Fig. 9. Comparing mode-locked Vs Q-switched cut quality in Silicon

For Silicon scribing experiments for the same average power of 2.5W at the sample surface various cutting depth achieved at a given cutting speed is shown in Fig. 10.

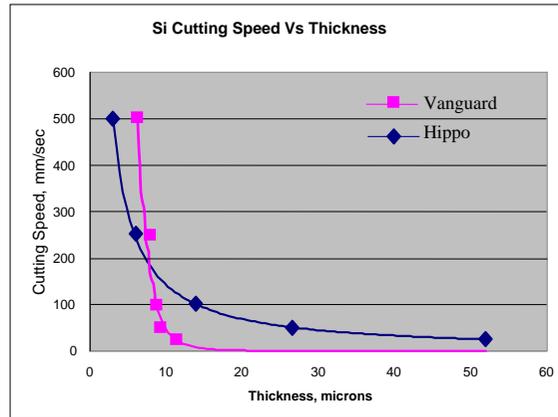


Fig. 10. Silicon machining comparing cutting depth achieved at a given cutting speed

As observed in the polyimide scribing, results in Fig. 10 show that for thinner films, less than 8 microns or so, the mode-locked laser is much better in material removal efficiency, and it allows scribing of Silicon at a much faster cutting speed. For the deeper scribing, however, the “digging out” of material gets much harder for low energy picoseconds pulses. Therefore, the scribing speed for both lasers becomes equal for about 8-micron deep scribes. Also, to scribe material above 8 microns q-switched laser does a better job than the mode-locked laser. Therefore, the mode-locked laser does a better job of scribing thinner Silicon films whereas for thicker films q-switched laser works better. Hence, for a given average power level there is a cross over point below which mode-locked laser is a better choice and above which the q-switched laser is a better choice for processing of Silicon. However, the cross over point for Silicon, at about 8 microns, is much lower than that observed for Polyimide, at about 80 microns for average laser power of 2.5W. We attribute this to higher thermal conductivity of Silicon.

4.3 Copper

For Copper machining also first thing that was observed was that for a given set of laser parameters, removing material in multiple passes at a higher scribing speed, rather than in an equivalent single pass scribing speed provided cleaner removal of material. Figure 11 shows the difference in scribes created using a Hippo laser for the same average speed for a different number of scans.

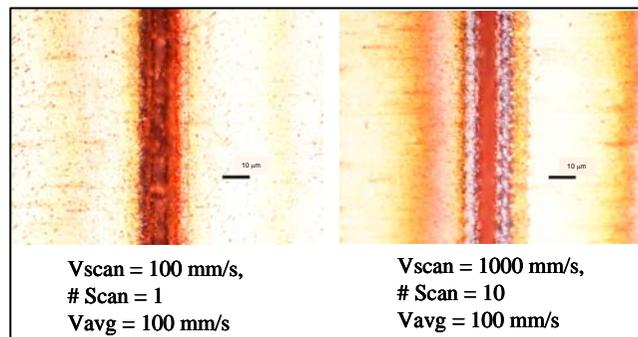


Fig. 11. Copper machining using a q-switched HIPPO laser at same average speed using single and multiple scans.

The same effect, to a lesser degree, of cleaner removal by multiple scans was also observed for Vanguard laser as shown in Figure 12.

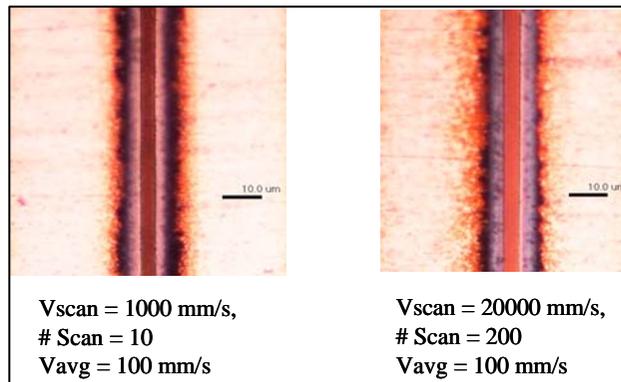


Fig. 12. Copper machining using a mode locked Vanguard laser at same average speed using multiple scans at different scanning speed.

Fig. 13 shows the difference in cut quality between the HIPPO and Vanguard lasers.

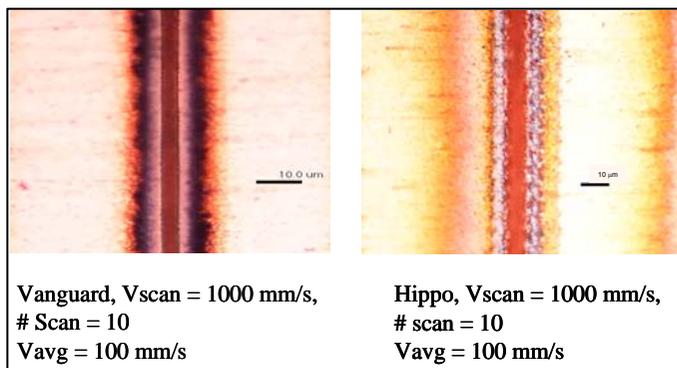


Fig. 13. Comparing mode-locked Vs Q-switched cut quality in Copper

For Copper scribing experiments for the same average power of 2.5W at the sample surface various cutting depth achieved at a given cutting speed is shown in Fig. 14.

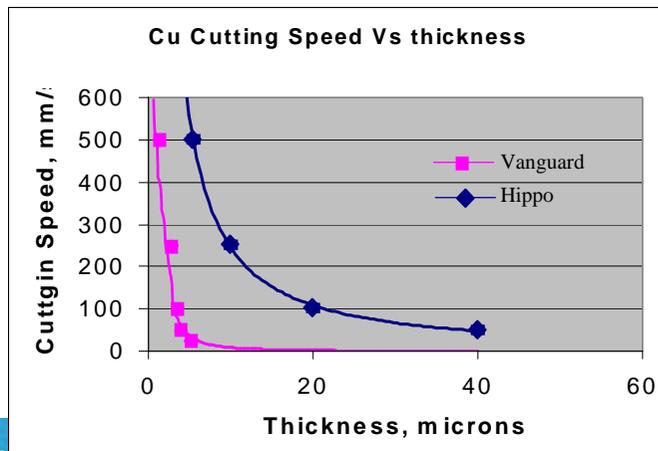


Fig. 14. Copper machining comparing cutting depth achieved at a given cutting speed

The results in Fig.14 show that for any given cutting speed in this study q-switched laser was much better in material removal efficiency than a mode-locked laser. Also, the mode-locked laser was able to scribe copper to only up to 5 microns depth. It is clear from the data that for material with a very high thermal conductivity, low energy pulses of mode-locked laser does not do a good job of material removal. The higher energy per pulse of a q-switched laser is needed to get over the thermal dissipation and do effective material removal.

5. CONCLUSIONS

General trend observed in the previous experiments were confirmed in the current study. Mode-locked laser seems to be more efficient than q-switched laser in machining material with a low thermal conductivity (such as polyimide) compared to material with a higher thermal conductivity (such as copper). For a given average laser power and material type there exists a “cross over” thickness below which mode-locked laser is usually more efficient in removing material and above which q-switched laser is more efficient. Mode-locked laser’s material removal efficiency improves as processing speed goes up regardless of material type, i.e. to get most out of a mode-locked laser, material should be processed at higher speed.

For Si and Cu - material removal through multiple high speed scans is cleaner than single low speed scan. Qualitatively features machined by both lasers look similar with varying degree of thermal effects to surrounding area.

Based on data we conclude that variation observed in machining performance between mode-locked laser and q-switched laser for various material types has to do with how heat dissipation is managed. In the mode-locked laser processing regime low (nJ/pls) energy pulses are impinged at high (MHz) repetition rate on the material, when material is moved slowly there is more time for thermal conduction and laser energy is not used efficiently and hence less laser energy is available for material removal. Where as when material is moved at a higher speed, less time is available for thermal conduction and hence laser energy is used more efficiently and more laser energy is used in removal of material. Hence in general for a higher cutting speed material removal efficiency of mode-locked laser is higher. In the q-switched laser processing regime high (mJ/pls) energy pulses are impinged at low (kHz) repetition rate on the material, so when material is moved slowly there is more available for thermal conduction with deeper thermal penetration that helps more material removal. Where as when material is moved at a higher speed, less time is available for thermal penetration and eventually pulse separation limits machining capability of a q-switched laser.

So for materials with low thermal conductivity – mode-locked laser is a better choice for material removal but for materials with higher thermal conductivity q-switched laser is a better choice.

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