MULTIPLE BEAM ULTRASHORT PULSE LASER MICROPROCESSING
(Invited paper)
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Abstract:
A problem identified in the use of ultra short pulse lasers for the processing of materials has been that, to work close to the ablation threshold and hence avoid thermal damage, a large percentage of the available laser energy must be attenuated. The surface ablation of materials, using multiple diffracted beams generated by a Spatial Light Modulator (SLM), driven by Computer Generated Holograms (CGH) and synchronised with a scanning galvanometer system, has been shown here to result in flexible and high throughput parallel processing. By using multiple low energy beams, derived from a single higher energy beam, more efficient use of the available laser energy is made and process time is significantly reduced. The results demonstrate high precision microprocessing, showing the potential for ultra short pulse laser parallel processing in real industrial application. A review of the background of the use of SLMs in parallel processing is given, followed by examples of applications investigated.

Key words: Femtosecond laser; Spatial light modulator (SLM); Computer generated holograms (CGH)

1. Introduction
During the last decade, ultra short pulse lasers have been used to obtain high precision surface microprocessing of different materials, e.g. metals and semiconductors [1-5]. Due to the ultra high intensity of focused femtosecond pulses (I > 10^{12} W/cm^2), nonlinear absorption can be induced at the focus leading to highly localised material ablation. In metals, when the input fluence, F, is kept in the low regime, a few times above the ablation threshold (F ~ 1 J cm^{-2}), heat diffusion during the temporal ultra short pulse width can be reduced to the nanometer scale, comparable to the optical skin depth [4-6]. Accordingly, the pulse energy used in ultrafast laser processing is often kept to the micro-joule level (10^{-6} J) for fine micro/nano-surface structuring due to the low and well-defined ablation thresholds. Consequently, high gain regenerative amplifier systems running at repetition rates ~ 1 kHz and providing milli-joule (10^{-3} J) level output pulse energy, have to be attenuated severely, thus severely limiting the useful throughput.

Generating parallel multiple beams, by spatially splitting an mJ level energy laser pulse into many lower energy µJ laser pulses is a novel and straightforward method to increase the efficiency and throughput of precision ultrafast laser processing. From multiple-beam interference [7-10] to micro-lens arrays [11-13], previous studies have demonstrated a number of approaches to create multiple beams to improve ultrafast laser microfabrication. Parallel processing with arbitrary multi-beam patterns holographically created by computer generated holograms (CGHs) using a Spatial light Modulator (SLM) was demonstrated by Hayasaki et al. [14, 15].

In this paper, dynamic ultrafast laser parallel processing using SLMs is demonstrated with a synchronization of real-time CGH playing and scanning galvanometer movement. The single beam with mJ pulse energy input on SLM is successfully diffracted into tens of desired beams, signifying the potential of this technique in industrial applications. In addition, a series of applications are demonstrated, showing great potential for applying this technique in industry.

2. Experimental
Fig.1 shows the schematic of the experimental setup with the 4f optical system, where a Clark-MXR CPA2010 laser system was employed, generating ultrashort laser pulses, at a pulse duration of 180fs, a wavelength of 775nm and a repetition rate of 1 kHz which were attenuated by a half wave-plate and a Glan laser polariser. After reflection on mirrors 1 and 2, the laser illuminated a reflective SLM Liquid Crystal on Silicon (LCoS) device with 1024 × 768 pixels (Holoeye LC-2500), oriented at < 10 angle of incidence. A beam expanding telescope, with magnification M ≈ 2, was used to reduce the average beam intensity on the SLM, where the CGHs were displayed. Lens 1 and Lens 2 were two BK7 plano-convex lenses with anti-reflection coating. Referring to Fig.1, since distance AB = BP = PM + MC = CN + ND ≈ f (≈ 300 mm), a 4f optical system with unity magnification was formed. Accordingly, at D, the complex field was identical with that at A. The zero order reflected beam
was spatially separated and blocked at Q. Just after D, the modulated beam, $u_h$, entered the 10 mm aperture of a scanning galvanometer system with a flat field lens ($f = 100$ mm). The proximity of the beam, $u_h$, (at D) to the input aperture of the galvanometer ensured that diffracted beams where transmitted cleanly to the substrate surface, while the flat field of the f-theta lens produced a near perfect focusing system. Substrates were mounted on a precision 4-axis (x, y, z, u) motion control system (Aerotech) allowing accurate positioning of the substrate surface at the laser focus.

![Fig. 1: Schematic of the experimental setup for the Clark-MXR CPA2010 laser with a 4f optical system](image)

### 3. Results and discussion

#### 3.1 Static CGH multiple beam microprocessing

Fig. 2 (a) shows optical micrographs of the surface structuring on silicon with an ‘LLEC’ pattern comprising 32 blind holes while Fig. 2(b) demonstrates a random spot pattern comprising 30 holes. Each hole pattern was micro-machined simultaneously on a silicon wafer by applying the calculated CGHs to create the desired geometries. The GL algorithm [16, 17], which is simple and computationally fast, was used to calculate CGHs producing multiple independent diffracted $+1$ order beams for processing. The incident pulse energy on the SLM was $E_p \sim 300 \mu$J. All diffracted spots had similar dimensions indicating accurate calculation of the CGH. The large hole above the main pattern of holes was generated by the zero order beam. The total input pulse energy was $\sim 300$ $\mu$J, measured before the aperture of the scanning galvanometer. The energy diffracted into each of the desired beams was $\sim 5$ $\mu$J.

![Fig. 2 (a): ‘LLEC’ pattern comprising 32 micro-sized holes [19]](image)

The measured hole size versus distance from the zero order hole in both ‘LLEC’ and random spots patterns is shown in Fig. 3. The uniformity of the diffracted beams is shown by the measurements of the ablated spot diameters using a Wyko NT1100 optical surface profiler: $\Phi_1 = 20.3 \pm 1.2$ $\mu$m (‘LLEC’ pattern) and $\Phi_2 = 21.7 \pm 1.1$ $\mu$m (random spots pattern). To avoid large variations in the required intensity distributions between spots, it is advantageous to avoid patterns with a high degree of symmetry [18].

The un-diffracted zero order beam containing approximately 50% of the input pulse energy was blocked by a metallic target at position Q (Fig. 1). Referring to Fig. 4, digital camera images show the holographically produced energy distribution of the ‘LLEC’ pattern on a paper screen near the Fourier plane. The $+1$ order beams contain the majority of the diffracted energy because the CGH was designed to enhance them, while -1 order beams with much lower energy ($<<$ material’s ablation threshold) leave the substrate unaffected. The lower two pictures of Fig. 5 demonstrate the absence of large holes showing that the zero order beam was successfully removed.

![Fig. 2 (b): Random spots pattern comprising 30 micro-sized holes [19]](image)

![Fig. 3: Hole size versus the distance from each diffracted spot to the zero order hole in both ‘LLEC’ and random spots patterns [19]](image)
Fig. 4: Demonstration of the enhancement of the +1 diffracted orders (LLEC pattern) combined with blocking the zero order beam using a small metallic target. The image shows intensity distribution on a paper screen taken with a digital camera. [20]

Fig. 5: The zero order beam removed when micro-structuring a silicon substrate with the ‘LLEC’ and random spots patterns [20]

3.2 Dynamic diffractive pattern microprocessing

While static holograms are useful and can be combined with the galvanometer system to demonstrate parallel processing with fixed spot geometry, processing by real time control of the CGHs would provide much greater flexibility for process configuration and applications, and is addressed in this section.

3.2.1 Response time of SLM

When addressing a series of CGHs in real time, the playing rate (i.e. the number of CGHs played per second) is significantly restricted by the response time, which is a period of time required to fade out the previous CGH (fall time) and build up a new one (rise time). In this section, the response time of the Holoeye LC-R 2500, one of the SLMs used for the present research, is investigated.

In the experiment, two CGHs, calculated by the GL algorithm, capable of generating three desired diffracted beams individually, were alternately displayed on the SLM at a 10 Hz refresh rate, whilst the laser was scanned in a straight line at a speed of 50 mm/s on a polished silicon sample by the scanning galvanometer. Fig. 6 shows an optical micrograph of the machined pattern on the silicon sample, where CGH1 was fading out and CGH2 was building up during the scanning. Due to the quick scanning speed, partially or completely separated single-pulse-machined craters (holes) were produced on the surface of the sample. Since the pulse repetition rate was 1 kHz, the period of time between two adjacent holes was 1 ms. On the left hand side of Fig. 6, towards the scanning direction, the size of the holes machined by the diffracted order beams decreases while, in contrast, the zero order machined holes increase in size. This indicates the fading out of the CGH1, where the diffracted pulse energy was gradually transferred back to the zero order beam. Similarly, the increase of the diffracted beam hole size and the decrease of the zero order beam hole size on the right hand side of the figure represent the time period when CGH2 was gradually building up and the pulse energy was re-diffracted to the desired multiple beams.

As shown in Fig. 6, by counting the number of order machined craters from A (with CGH1 starting to fade out) to B (with CGH2 built up completely), the response time was estimated to be ~ 27 ms (fall time ~ 17 ms, rise time ~ 10 ms), which matches reasonably the value given in the manual for the Holoeye LC-R 2500 SLM shown in Fig. 7 i.e. 28 ms (fall time ~ 18 ms; rise time ~ 10 ms).
This response time restricts the maximum CGH playing rate to < 50 Hz. However, if there is a little change in the position of the desired diffracted beams when building up the successive CGH, 50 Hz rate of CGH playing also allows perfectly good machining results in parallel processing.

3.2.2 Microprocessing by real time playing CGHs

Fig. 8 (a) shows a pattern comprising 121 holes completed by real time playing of 15 stored CGHs at 20 Hz refresh rate, and Fig. 8 (b) demonstrates the formation of the pattern, which was completed within 0.75 s. The incident pulse energy on the SLM was $E_p \sim 300 \, \mu$J.

By combining real time control of the CGHs with scanning, diffracted multi-beam processing has significant potential to produce complex surface micro-machining patterns by dynamic control of the optical landscape. Fig. 9 (a) and (b) illustrate this on a polished Ti6Al4V substrate where 6 micro-channels, a-f, were generated by applying the appropriate CGHs at 50 Hz refresh rate while simultaneously scanning the diffracted spots at a speed of 1mm/s. The resulting micro-channels were ~ 40 μm wide and ~ 10 μm deep. The large channel on the top of the figure was machined by the zero order beam.
10 (a), while Fig. 10 (b) shows the pattern with zero order removed. The pulse energy incident on the SLM was $E_p \sim 150 \mu J$, and the measured hole diameter ($\Phi \sim 25 \mu m$) and depth ($\sim 2.3 \mu m$) corresponded to an exposure time of 200 ms (i.e. 200 pulses), with pulse energy $E_p \sim 5 \mu J$ in each +1 diffracted order beam. As each CGH generated more than 15 higher order holes simultaneously, a throughput gain factor $G > 15$ was demonstrated compared to single beam processing in this case.

The material samples chosen for this research were silicon wafer (a semiconductor widely used in the fabrication of integrated circuit and other micro devices) and Ti6Al4V (an alloy extensively used in aerospace and bioscience sectors). Both materials have a relatively low threshold for femtosecond laser pulse induced ablation. Thus, when using single beam micromachining, extensive attenuation may be required to provide low pulse energy i.e. just above the threshold, hence resulting in low processing efficiency. However, the results reported here for parallel processing demonstrate great advantages in term of increasing both processing throughput and efficiency.

3.3 Applications

Since sufficient laser output from commercial laser sources is currently exceeding single beam process requirements, parallel processing with multiple beams could provide an easy route for up-scaling processing speed and suppress manufacturing costs. The methods described for parallel processing of materials with high speed, dynamic control and great flexibility, facilitate applications in the following areas:

3.3.1 Silicon wafer scribing Fig. 11 depicts the microscopic image of a silicon sample laser scribed using 15 asymmetric beams. A picosecond laser system (High-Q IC-355-800nm) generating 10ps pulse width and 532nm wavelength laser pulses at 5kHz repetition rate was employed for the processing. A dielectrically coated Hamamatsu X10468-04 SLM providing $\sim 90\%$ reflectivity at 532 nm wavelength was used to generate diffracted multiple beams. Picosecond laser systems with compacted design and much lower price have demonstrated similar machining quality comparable to complex and expensive femtosecond lasers [25]. With narrower spectral bandwidth (here $\tau \approx 10$ ps, $\Delta \lambda \approx 0.1$ nm), the chromatic distortion of the diffracted beams can be eliminated [21].

The 15 beams with total incident pulse energy of 21 $\mu J$ (1.4 $\mu J$/beam) were scanned orthogonally with two CGHs at 10 mm/s to produce the cross hatched pattern. The scribed lines were $\sim 500$ nm deep and 14 $\mu m$ wide, with a period $\Lambda$ of 86 $\mu m$. No thermal damage to the surrounding area was observed.

Fig. 10 (a): ‘OPTICS’ pattern with zero order holes, completed by 7 CGHs applied at appropriate positions using the galvanometer scanner [20]

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Fig. 10 (b): ‘OPTICS’ pattern with zero order holes eliminated (The insert 3D pictures were measured using Wyko NT1100 optical surface profiler, illustrating the depth of the holes) [20]

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Fig. 11: Multiple beam parallel processing of a silicon sample. [22]

![Fig. 11: Multiple beam parallel processing of a silicon sample. [22]](image)

Beam scanning with a different number of spots per line mimics a variable spot overlap and can produce variable controlled ablation depth, as shown in Fig. 12. Ten beams were arranged in a 4-3-2-1 pattern so as to achieve selective ablation with a single scan at different positions. The small red circles in Fig. 12 (a) denote the 10-beam
The pattern used for silicon scribing. The total pulse energy ($E_p$) incident on the sample was 18 µJ, hence giving $E_p \sim 1.8$ µJ to each of the diffracted beams. Fig. 12 (b) and (c) demonstrate the machining results on a silicon wafer with 532 nm laser wavelength, 5 kHz repetition rate and 1 mm/s scanning speed, where different ablation depths were obtained.

![Scan direction](image1)

**Fig. 12 (a):** Schematic of selective ablation using a different number of spots per line to produce different ablation depth. [22]

![Scan direction](image2)

**Fig. 12 (b):** Micrograph of 10 beams selective ablation on silicon. The red circles represent the positions of the 10 beams. [22]

![Scan direction](image3)

**Fig. 12 (c):** Cross-sectional of surface profile of the 10 beam selective ablation on silicon. The scribe line 1, 2, 3 and 4 are consistent with those labelled in Fig. 7.2.4 (b). [22]

3.3.2 Patterning of organic light emitting diodes (OLED) materials Laser patterning of OLED is a key industrial process in the manufacturing of OLED displays or solid-state lighting foils [26]. Ultra short pulse lasers are of particular interest for this application, as they enable selective removal of OLED layers with very low energy density requirements, thus avoiding damage to the target. Since the output energy from commercial laser sources is currently exceeding single beam process requirements, parallel processing with multiple beams could provide a novel route for up-scaling processing speed and reduce manufacturing costs. Hence SLMs could be employed for high throughput precision patterning of OLED materials (metal cathode and ITO anode) on flexible and glass substrates.

3.3.2.1 Cathode patterning OLEDs comprise multiple layers of different materials and so each layer may have a different ablation threshold, (for example, the top cathode layer, aluminium, has a lower ablation threshold than the underlying anode layer, ITO film [27]). Therefore, it is important to control the laser fluence in order for it to be high enough to completely remove aluminium, but lower than the ablation threshold of the ITO. Multi-beam scribing of an OLED sample using 15 beams with 532 nm wavelength produced by the X10468-04 SLM is shown in Fig. 13. The laser pulse energy, repetition rate and scanning speed were 12 µJ, 5 kHz and 30 mm/s, respectively. Only a single scan was conducted, resulting in multiple scribing lines with the period of 86 µm, a line width of ~ 10 µm and a depth of ~ 300 nm, which is the interface between the organic layer and the anode.

![Parallel processing of an OLED sample using 15 beams.](image4)

(a) Optical micrographs; (b) Cross-sectional profile of a single scribing line. [22]

3.3.2.2 Anode (ITO) patterning Since the absorption of ITO material in the NIR region is stronger than that in the visible region, a picosecond laser with a wavelength of 1064 nm was used for patterning of ITO on glass samples. Fig. 14 demonstrates a microscope image and surface profile of the ITO sample that was ablated using 5 beams ($\lambda = 1064$ nm) generated by a Hamamatsu X10468-03 SLM providing ~ 90% reflectivity. The incident pulse energy on the sample was 16 µJ with 5 kHz repetition rate, 15 mm/s scanning speed. Only a single scan was performed. The period $\Lambda$ was 65 µm. As illustrated, the scribing line had a depth of ~ 60 nm and a width of 14 µm, and showed a flat bottom area that indicates complete removal of the ITO film. Placing the spots closer and using lower laser pulse energies can reduce the period and the scribing width, respectively. There was no thermal damage to the surrounding area observed.
Fig. 14: Parallel processing of ITO thin film sample using 5 beams. (a) Optical micrographs; (b) Cross-sectional profile of a single scribe. [22]

4. Conclusions

This paper demonstrates multiple beam ultrafast laser parallel microprocessing using SLMs. The desired diffracted beam patterns are modulated by CGHs, calculated by appropriate algorithms. The surface structuring using multi-beam patterns synchronised with a scanning galvanometer system shows flexible and high throughput parallel processing. The results reveal high precision microprocessing with higher efficiency, showing the potential of ultrafast laser parallel processing for industrial applications. Future work will focus on exploring the maximum power handling capability of the SLMs, hence knowing the viable energy diffracted to the desired multiple beams, and which would be a significant step towards transferring this parallel processing technique from laboratory to industry.

Acknowledgments

The authors gratefully acknowledge the support of the North West Development Agency (NWDA) and the Technology Strategy Board (TSB) under the project PARALASE (Prog. No.: TP11/LLd/6/I/AF063B), and kind help from Prof. Miles Padgett and Dr. Jonathan Leach in the Department of Physics and Astronomy at the University of Glasgow, Scotland. One of the authors, Zheng Kuang, would like to thank the Scholarship of Overseas Research Students Award Scheme (ORSAS) and the University of Liverpool Graduate Association (Hong Kong) for providing financial support for his PhD study at the University of Liverpool.

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