Diffractive multi-beam surface micro-processing using 10 ps laser pulses

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1. Introduction

Ultrashort pulse laser micro-structuring is opening up application from integrated optics, through multi-photon induced refractive index engineering to precision surface modification for silicon scribing and solar cell fabrication [1–3]. When temporal pulse τ < 10 ps, ablation thresholds are low and well defined and collateral surface damage can be strongly reduced due to picosecond timescale electron-lattice energy coupling [4–8]. Parallel processing using diffractive multiple beams generated by a spatial light modulator (SLM) has been demonstrated to increase throughput and efficiency of ultra-fast laser processing [9–15]. By synchronisation with a scanning galvo, diffractive multiple beams processing shows further flexibility and potential industrial applications [14,15]. Nevertheless, using a femtosecond laser (τ ≈ 180 fs), the finite laser bandwidth (Δλ ≈ 5 nm) can significantly alter the intensity distribution of diffracted beams at higher angles resulting in elongated hole shapes [15].

With this limitation in mind, a picosecond laser system with much narrower spectral bandwidth (τ ≈ 10 ps, Δλ ≈ 0.1 nm) is employed here for diffractive multiple beam processing. Compact solid state picosecond laser systems (τ < 15 ps) with high pulse energy, average power and repetition rate, have shown advantages over femtosecond system for high precision micro-machining [7,8]. This paper demonstrates that the distortion of intensity profile at high diffractive angle is eliminated due to the narrower spectral bandwidth of the laser source. The drilled holes perfectly keep their round shape (eccentricity: e < 1.04) when applying large diffractive angle (θ ≈ 1.27°). Finally, high power (2.5 W) parallel processing with 25 diffracted beams and laser repetition rate applied (f ≈ 20 kHz), demonstrates industrial level precision laser micro-processing.

2. Experiment

Fig. 1 shows the schematic of the experimental setup. The 1064 nm, 10 ps laser output (High-Q IC-355-800 nm, 0–50 kHz) beam traversed a half wave plate used for adjusting the linear polarization direction, a beam expander (M ≈ 3), and after reflection on mirrors 1 and 2, illuminated a reflective phase only SLM (Hamamatsu X10468-03) liquid crystal on silicon (LCoS) device with 800 × 600 pixels and dielectric coated for 1064 nm wavelength (reflectivity, η ≈ 95%), oriented at < 10° angle of incidence. Directed by the LCoS, the modulated beam entered a scanning galvanometer with f = 100 mm flat field of f-theta lens (Nutfield) producing a near perfect focusing system. Substrates were mounted on a precision 5-axis (x, y, z, p, q) motion control system (Aerotech) allowing accurate positioning of the substrate surface at the laser focus. The spectral bandwidth, Δλ ≈ 0.1 nm at
3. Results and discussions

3.1. Defocus zero order beam

The un-diffractive zero order beam which otherwise would generate unwanted surface damage, can be removed at the Fourier plane of a 4f telescope optical system [9,12,13,15]. Alternatively, in this work, the zero order beam was significantly defocused at the processing plane by adding a Fresnel zone lens (FZL) onto the computer generated hologram (CGH). The focal length \( f_1 \) of FZL can be easily adjusted by the software developed by Holoeye [19] with friendly interface (Fig. 2). Only diffracted beams were converged \( (f_1 > 0) \) or diverged \( (f_1 < 0) \) by the FZL while the zero order beam was unaffected hence separating the focal planes of the diffracted from the zero order beam (Fig. 3). The beam matrix equation given in Fig. 3 describes the propagation of diffracted beam from the LCoS surface (A) to its focal plane (B), where \( X_{A} \) and \( X_{B} \) are the distances of the beam from the axis, while \( \theta_{A} \) and \( \theta_{B} \) are the gradients of the beam with respect to the axis at the position A and B, respectively. Since \( \theta_{A} = 0 \) and \( X_{A} = 0 \), the focal plane separation \( (\Delta d) \) can be calculated by the following equation derived from the beam matrix equation:

\[
\Delta d = |d_2 - f_2| = \left| \frac{f_1 f_2 - f_2 d_1}{f_1 + f_2 - d_1} - f_2 \right|
\]

where \( d_1 \approx 200 \text{ mm} \) was the distance between LCoS and \( f \)-theta lens, and \( f_2 \approx 100 \text{ mm} \) was the focal length of \( f \)-theta lens. Thus:

\[
\Delta d \text{ (mm)} = \left| \frac{100 f_1 - 20000}{80 + f_1} - 100 \right|
\]

A slightly defocused zero order beam could still damage the sample because it contains approximately 50% of the input pulse energy which was much stronger than any of the diffracted orders [14]. Accordingly, \( f_1 \) must be adjusted carefully to allow sufficient separation \( (\Delta d) \) so that the fluence at the substrate is below the damage threshold. Fig. 4(a) demonstrates a CGH calculated by ‘gratings and lenses’ algorithm [16–18] to generate eight first order identical beams and its computational reconstruction, while (b) shows the micro-machined results on Ti6Al4V using the CGHs which were superimposed by FZLs with different \( f_1 \) to adjust \( \Delta d \). Fig. 4 (b) shows that the defocused zero order beam still damaged the sample when the separation \( \Delta d = 1 \text{ mm} \) (middle lower

![Fig. 1. Experimental setup.](image1)

![Fig. 2. Interface of the software developed by Holoeye [19], which can easily superimpose and adjust the phase of FZL.](image2)

![Fig. 3. The schematic showing the way to separate the focal plane of diffracted beams from the zero order. The added FZL lens 1, can work as either positive lens (upper) or negative lens (lower) to obtain the separation, \( \Delta d \). The beam matrix equation below describes the propagation of diffracted beam from LCoS surface (A) to its focal plane (B).](image3)
3.2. Spectral bandwidth effect on diffracted beam shape

Fig. 5(a) demonstrates a series holes drilled on a silicon sample using 10 ps (∆λ ≈ 1064 nm, ∆λ ≈ 0.1 nm) pulses when varying the diffractive angle, while, in Fig. 5(b), the 2D (left) and 3D (right) micrographs with large magnification clearly shows the reasonably round hole shape when applying large angle of diffraction (θ ≈ 1°). A graph, demonstrating the eccentricity e = a/b of these drilled hole shape as a function of diffractive angle is plotted in Fig. 6, and shows that e increases only very modestly, e < 1.04. Fig. 7 shows that there is a negligible variation of ablation depth (1000 pulses, E_p ≈ 5 µJ) with increasing angle of diffraction, demonstrating a high degree of reproducibility of the diffractive multi-beam processing. The above results indicate that the elongation of diffracted beam shape caused by chromatic distortion [15] can be eliminated by employing picosecond laser pulses (τ ≈ 10 ps) with narrower bandwidth hence allowing constant ablation rate.

3.3. High power parallel processing with high repetition rate at f = 20 kHz

With the ps system (τ ≈ 10 ps) operating at high repetition rate (f = 20 kHz) and maximum output (P_{average} ≈ 2.5 W), parallel processing is demonstrated, using 25 diffractive beams pattern,
created by a CGH calculated by 2D Gershberg-Saxon (GS) algorithm using a LabVIEW program [17]. The schematic given in Fig. 8 demonstrates the design of the beams pattern and the method of scanning. (The vertical distance between two adjacent spots was 100 μm; by repeatedly scanning the pattern with 50 μm vertical offset each time, multiple micro-channels with 50 μm intervals can be obtained.)

Fig. 5. (a) A series holes drilled on a silicon sample when varying the diffractive angle. (b) The 2D (left) and 3D (right) micrographs with large magnification, showing the shape of the hole, fabricated by single 10 ps pulse, when applying large diffractive angle, \( \theta > 1^\circ \).

Fig. 6. The graph demonstrating the eccentricity \( e \) of hole shape drilled by 10 ps when varying the angle of diffraction.

Fig. 7. The graph demonstrating the variation of ablation depth using one thousand 10 ps pulses (\( E_p \approx 5 \mu J \)) when varying the angle of diffraction.

Fig. 8. The schematic showing the design of the 25 beams pattern and the method of scanning. (The vertical distance between two adjacent spots was 100 μm; by repeatedly scanning the pattern with 50 μm vertical offset each time, multiple micro-channels with 50 μm intervals can be obtained.)

4. Conclusion

Diffractive multiple beams micro-processing using 10 ps laser pulses has been demonstrated in this paper. The zero order beam is eliminated by adding a Fresnel zone lens (FZL) to defocus the undiffracted beam using simpler experimental setup. The machined holes are almost perfectly round, independent of angle of diffraction hence showing the obvious advantage of parallel processing using ultrashort pulses with picosecond temporal pulse length with narrow spectral bandwidth. Furthermore, simultaneously scanning multiple diffractive beams ($n = 25$) containing >1.2 W average power with higher repetition rate (up to) $f = 20$ kHz demonstrates high-throughput surface microstructuring by creating an “effective” repetition rate of 500 kHz without restrictive Galvo scan speeds.

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