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Multi imaging-based beam shaping for ultrafast laser-material processing using spatial light modulators

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ABSTRACT

An imaging based beam shaping technique combined with parallel beam processing has been demonstrated. Binary and intensity masks have been designed and applied on phase only spatial light modulator (SLM) to shape the input laser beam in the desired profile and intensity distribution. A second SLM with a computer generated hologram(CGH) applied was used to split the incident picosecond laser beam. Hence, the laser beam was effectively converted to required target shape, intensity distribution and a separated pattern then reconstructed at the image plane of a focusing lens. The machined footprints on a polished Titanium (Ti6Al4V) substrate accurately match the desired beam in shape and depth distribution.

1. Introduction

Ultrafast lasers are increasing in precision manufacturing as it can be regarded as a high quality tool for micro-processing on various materials like metals [1,2], semiconductors [3] and dielectrics [4]. Most of the laser processing used Gaussian beams and more and more researcher investigated the laser processing with different shaped laser beams and intensity [5,6]. A single spatial light modulator (SLM) has been used for beam shaping with computer generated holograms (kinoform) under high input power [7].

Parallel processing using diffractive multiple beams generated by a spatial light modulator has been studied to improve the thoughput and efficiency of ultrafast laser processing [8,9]. By synchronisation with a scanning galvo, parallel processing shows more flexibility and potential in industrial applications [10,11].

Another characteristic of ultrafast laser material processing is that the shape of the ablated area is very close to the laser beam intensity distribution due to a well defined ablation threshold coupled with the absence of melt. A number of beam shaping studies have been motivated by this approach [12]. The use of amplitude mask projection with diffractive optical elements (DOEs) [13] and deformable mirrors [14], demonstrate effective shaping of ultrashort pulse laser beams. For example, multiple annular beams were generated at the focal plane for high speed picosecond laser micro-drilling of stainless steel foil with diffractive axicon phases using a spatial light modulator (SLM) [15].

An interesting novel imaging-based amplitude beam shaping technique using a spatial light modulator has been recently demonstrated where arbitrary shapes and flat top beam can be obtained by grey level geometric masks at the diffraction near-field then reconstructed at an imaging plane with a size comparable with the beam waist at the focal plane [16,17].

In this paper, beam shaping combined with parallel processing to generate multiple shaped beams is presented with two SLMs for the first time. Both binary and intensity grey level geometric mask have been used to fully shape the ultrashort pulsed input laser beam to the outline profile and intensity distribution. After a long beam path, a second SLM has been used for beam splitting by computer generated hologram(CGH). The multiple beam shapes were then reconstructed at the image plane of an f-theta lens (f~ 100 mm).

2. Experimental and methodology

2.1. Experimental setup

A schematic of the experimental setup is shown in Fig. 1. The laser source is a custom made Nd:VAN seeded regenerative amplifier (High-Q IC-355-800 ps, Photonic Solutions) with output pulse duration $\tau = 10$ ps, wavelength $\lambda = 1064$ nm, repetition rate PR$F = 10$ kHz and beam diameter d ≈ 2.7 mm. The beam passes through a half wave plate and polarizer used for adjusting both power and polarization direction (45°), a beam expander (M ≈ × 3) and directed by two plane mirrors to the first

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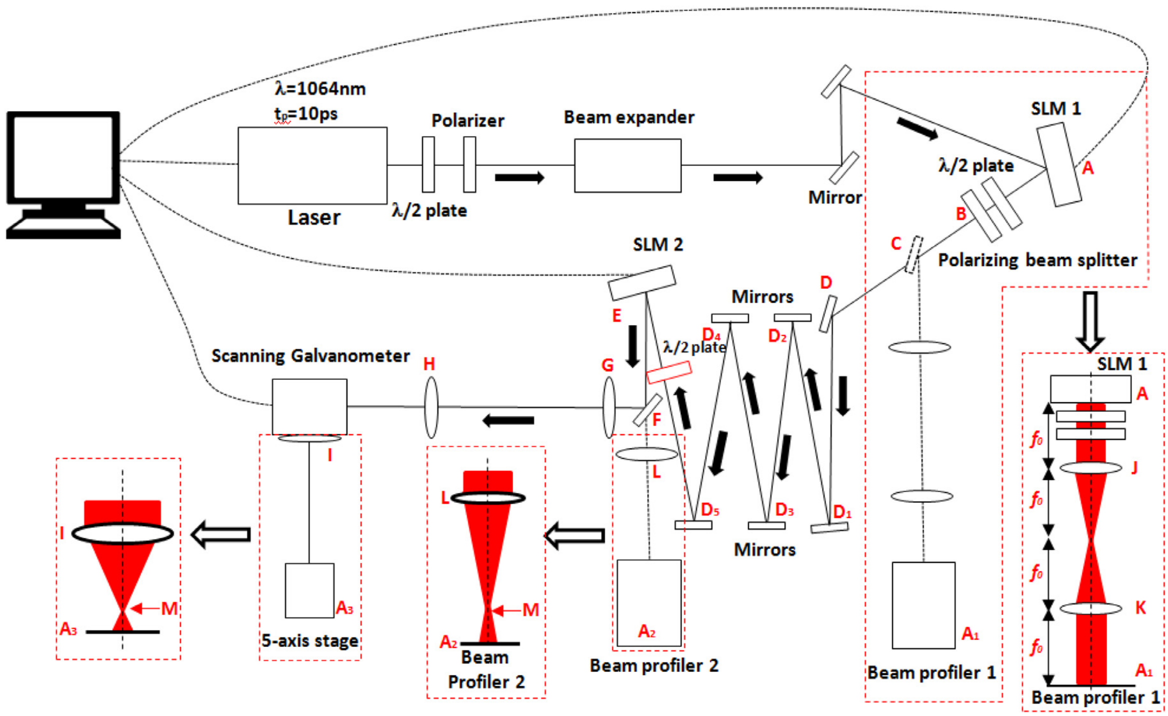

Fig. 1. Experimental setup.

reflective, liquid crystal SLM1 (Hamamatsu X13138-5785, 1280 × 1024 pixels, fill factor 96%) at low angle of incidence <10°.

The SLM1 (A) contains a parallel-aligned liquid crystal layer. An active matrix circuit is formed on the silicon substrate for applying appropriate voltages to pixel electrodes. Pure phase modulation of the incident light can be achieved when aligning the incident polarization parallel to the orientation of the liquid crystal while polarisation modulation results when incident polarisation is 45°. A polarizing beam splitter (B) combined with a half wave plate were placed after SLM1 to modulate the laser beam intensity for the onward beam shape.

When observing the beam profile after shaping, the beam was reflected by a flip mirror (C) and 4f system with two positive lenses (focal length: f_o = 200 mm) to reach beam profiler 1 (Thorlabs BC106-VIS). When processing, the flip mirror was removed and the beam traversed a long beam path (L = 4.3 m) by multiple reflected mirrors (D – D_5) to reach the second reflective phase only SLM2 (Hamamatsu X10468-03, 800 × 600 px, fill factor 98%).

Before SLM2, a half wave plate has been added to modulate the polarization horizontal relative to SLM2 for the onward multiple beam generation. After the SLM2, the beam was reflected by a flip mirror (F) to a scanning galvanometer (Nutfield XLR8-10) and f-theta focusing lens ($f_{f\text{-}}\theta$ = 100 mm). Lens G and lens H consists a 4f-system. M is the focal point. Machining samples were mounted on a five-axis (*x,y,z,u,v*) motion control stage (Aerotech) placed under the *f*-theta lens. When observing the beam profile after beam splitting, the flip mirror was removed to let the beam pass through a positive lens (focal length: f_o = 750 mm) to reach the second CCD camera and beam profiler (Spiricon SP620U) placed at the image plane of the lens. Hence, the desired beam shape with multi-beams could be observed before material processing.

2.2. Beam shaping using a SLM1

The setup of the intensity modulation system contains a 45° linear polarized incident laser beam, a Hamamatsu X13138-5785 SLM with a half wave plate and a polarizer. The setup can be expressed as a Jones vector noted *J(x,y)*, where x and y are the horizontal and vertical co-ordinates across the beam profiles. A full derivation for the resulting electric field amplitude using the optical properties of the setup gives:

$$J(x,y) = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \times \begin{pmatrix} cos2\theta & sin2\theta \\ sin2\theta & -cos2\theta \end{pmatrix} \times \begin{pmatrix} e^{i\emptyset(x,y)} & 0 \\ 0 & 1 \end{pmatrix} \times \begin{pmatrix} \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}} \end{pmatrix} \quad (1)$$

where *ϕ(x,y)* related to grey level is the phase delay induced with the first SLM and *θ* is the angle of the fast axis of half wave plate. The intensity of the output can be derived from Eq. (1) given by $J(x,y)^2$

$$I = \frac{1}{2}\begin{pmatrix} cos2\theta e^{-i\times\emptyset(x,y)} + sin2\theta & 0 \end{pmatrix} \times \begin{pmatrix} cos2\theta e^{i\times\emptyset(x,y)} + sin2\theta \\ 0 \end{pmatrix} = \frac{1}{2} + \frac{1}{2} sin4\theta cos\emptyset \quad (2)$$

where *I* is the transmission efficiency. When *I* = 1 the laser beam is passed through the polarizing beam splitter (B) without loss, when *I* = 0, the polarizing beam splitter directs all the intensity to a beam dump at a side port. As shown in Eq. (2), when $\theta = \frac{3}{8}\pi$, $I = \frac{1}{2} - \frac{1}{2}cos\emptyset$, which means that using this method, the transmitted relative intensity can be adjusted from 0 to 1 (as with the incident beam), see Fig. 2. The measured values in Fig. 2 have been taken from beam profiler 1. Variable grey level values on SLM1 correspond to different transmitted powers at A_1. Each measured power can then divided by the measured maximum power. The transmission efficiency curve can then be plotted. The theoretical values are based on the calibration data for the device from the manufacturer. Based on the equation $I = \frac{1}{2} - \frac{1}{2}cos\emptyset$, the corresponding theoretical curve can be extracted.

2.3. Outline shape and intensity distribution design

The measured values have been used for beam shaping. Both the binary and grey level masks were created and applied to the first SLM.