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Ultrafast laser beam shaping for material processing at imaging plane by geometric masks using a spatial light modulator

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ABSTRACT

We have demonstrated an original ultrafast laser beam shaping technique for material processing using a spatial light modulator (SLM). Complicated and time-consuming diffraction far-field phase hologram calculations based on Fourier transformations are avoided, while simple and direct geometric masks are used to shape the incident beam at diffraction near-field. Various beam intensity shapes, such as square, triangle, ring and star, are obtained and then reconstructed at the imaging plane of an f-theta lens. The size of the shaped beam is approximately 20 μm, which is comparable to the beam waist at the focal plane. A polished stainless steel sample is machined by the shaped beam at the imaging plane. The shape of the ablation footprint well matches the beam shape.

1. Introduction

In the last two decades, ultrafast lasers have been widely used for high precision and high quality material micro-processing. Materials ranging from metals [1,2], semiconductors [3], dielectrics [4–6] to biological tissues [7,8] can be processed by ultrafast laser pulses with a very small heat affected zone around the irradiated area. In recent years, the price of commercial ultrafast lasers has decreased rapidly and the laser system becomes more and more compact. Nowadays, some type of ultrafast laser systems, such as high repetition rate picosecond fibre laser systems, have been increasingly employed by manufacturing industries.

Due to the well defined ablation threshold, one of the characteristics of ultrafast laser material processing is that the shape of the processed area is very close to the laser beam's intensity distribution. This has motivated some efforts in the field of ultrafast laser beam shaping. From the use of amplitude mask projection and diffractive optical elements (DOEs) [9] to deformable mirrors [10], different technique has been attempted to shape ultrafast laser beams for various applications. Multiple annular beams were generated at focal plane by us recently for ultrafast laser micro-drilling with diffractive axicon phases using a spatial light modulator (SLM) [11]. Sanner et al. successfully obtained top-hat, doughnut, square, and triangle beam shapes at focal plane by programmable wave-front modulations using a nonpixelated optically addressed light valve [12,13]. However, to produce a desired shape at focal plane (i.e. far field), the phase modulation to the incident laser beam is complicated. Although algorithms based on time-consuming iterative calculations, such as Gerchberg and Saxton [14–16], were attempted to solve the issue, the accuracy was still not perfect due to the complexity nature of light diffraction.

In this paper, we demonstrate an original ultrafast laser beam shaping technique for material processing using a spatial light modulator (SLM). Complicated and time-consuming diffraction far-field phase hologram calculations based on Fourier transformations are avoided, while simple and direct geometric masks are used to shape the incident beam at diffraction near-field. Arbitrary beam intensity shapes can be easily obtained and then reconstructed at the imaging plane of an f-theta lens. The size of the shaped beam is approximately 20 μm, which is comparable to the beam waist at the focal plane. A polished stainless steel sample is machined by the shaped beam at the imaging plane. The shape of the ablation footprint well matches the beam shape.

2. Experiment and methodology

2.1. Experimental setup

A schematic of the experimental setup is shown in Fig. 1. A laser beam output (beam diameter: Dia. ≈ 1 mm, pulse duration: $t_p = 20$ ps, wavelength: $\lambda = 1064$ nm, and repetition rate:

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0143-8166/

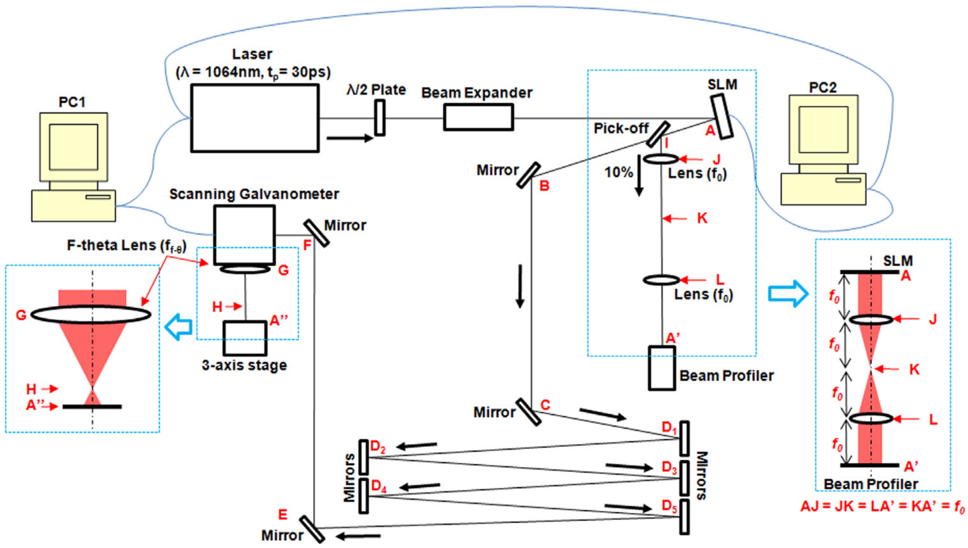

Fig. 1. Experimental setup.

R=200 kHz) from a picosecond fibre laser system (Finanium) is passed through a half wave plate used for adjusting the linear polarisation direction, a beam expander (M ≈ ×5), and illuminated on a reflective SLM (Holoeye LC-R 2500), oriented at $<10°$ angle of incidence. A pick-off (1%) beamsplitting mirror, placed after the SLM, reflected the beam through two positive lenses (focal length: f_0=200 mm) formed 4f system to a CCD camera-based laser beam profiler (Thorlabs) to observe the reconstructed beam shape. After the SLM, the laser beam travelled a long distance by multiple reflections on a series of mirrors, passed through a scanning galvanometer and reached a focusing F-theta lens ($f_{f-\theta}$=100 mm). Machining samples were mounted on a three-axis (x, y, z) motion control stage (Aerotech), placed under the F-theta lens.

2.2. Shaping observation using a beam profiler

The SLM (Holoeye LC-R 2500) modulates both phase and amplitude of the input beam. To obtain maximum amplitude modulation, the input polarisation (linear) was set to be vertical. A binary (black & white) mask used to shape the input beam intensity is demonstrated in Fig. 2(a), while a graph showing the SLM reflectivity versus mask grey level is given in Fig. 2(b). Since the black geometry (i.e. grey level=255) in the mask has a relatively higher reflectivity, the mask works as a geometric intensity filter and the beam is shaped to the geometry in the near field after the SLM. However, the beam does not maintain the shape when propagating due to the diffraction. The 4f system (AJ=JK=KL=LA′=f_0) between the SLM and the beam profiler was established to reconstruct the beam shape at A–A′.

2.3. Shaping reconstruction at imaging plane of focusing lens

The beam shape at A was also reconstructed at the imaging plane of the F-theta lens, A″. As shown in Fig. 1, five extra mirrors, D_1–D_5, were added to significantly increase the distance from the SLM to the focusing F-theta lens, i.e. the object distance. The purpose of this was to reconstruct the shape to a small size comparable to the beam waist. The position of the imaging plane A″ can be calculated, based on the thin lens imaging equation below,

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f} \quad (1)$$

where, $u\approx 15000$ mm is the object distance, i.e. the distance from the SLM(A) to the F-theta lens(G), f=100 mm is the focal length of F-theta lens and v is the image distance, i.e. the distance from the F-theta lens (G) to the image plane (A″),

$$v=\frac{fu}{u-f}\approx 100.67\ \text{mm} \quad (2)$$

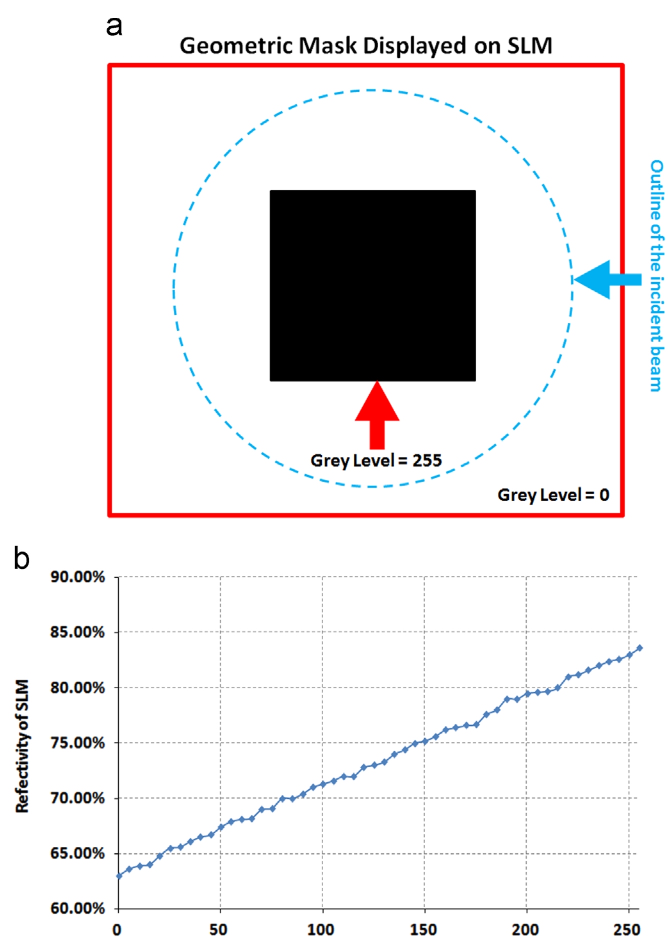

Fig. 2. (a) A binary geometric mask (black & white) used to shape the input beam intensity, (b) A graph showing the SLM reflectivity versus mask grey level.