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High-precision femtosecond laser beam shaping in material processing

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Abstract. Laser beam shaping is the process of modulating the amplitude and phase of a laser beam. With the development of the spatial light modulator, laser beam shaping can modulate the light field to arbitrary pattern dynamically via the computer-generated hologram (CGH). Otherwise, femtosecond laser is widely used in material processing owing to its high peak power, low hot effect and nonlinear effects. However, femtosecond laser is not strictly monochromatic, which will introduce dispersion when femtosecond laser diffracted by a spatial light modulator, and deteriorate the effect of beam shaping. Here we present a method of high-precision femtosecond laser beam shaping. Experimental results confirm that the proposed method can be used to shape femtosecond laser beams into arbitrary patterns in the whole field of view (FOV) with the resolution near the optical diffraction limit.

1. Introduction

Laser beam shaping has been widely applied in material processing, such as laser drilling[1], cutting[2], welding[3], and laser direct writing[4]. Researchers usually use the spatial light modulator (SLM), for example, the phase-only liquid crystal spatial light modulator (LC-SLM) to generate arbitrary amplitude and phase profiles at a shaping rate of 60 Hz[5]. Alternatively, the digital micromirror device (DMD) achieves arbitrary beam shaping with a significantly higher rate up to 32.5 kHz[6]. Owing to the high peak power, low hot effect and nonlinear effects, femtosecond laser has been developed rapidly in the last decades. However, dispersion will be introduced when femtosecond laser passing through the SLM because of its nonmonochromatic nature[7]. Researchers have made a great effort to achieve higher resolution laser beam shaping. The general method is using a grating to compensate the dispersion introduced by the SLM[8]. However, the grating only compensates the dispersion in the centre of the field of view. In other fields of view, remaining dispersion is not compensated yet, resulting the laser beam deteriorated. In this paper, we propose a method of high-precision femtosecond laser beam shaping based on the DMD, which can compensate the dispersion of femtosecond laser in the whole field of view.

2. Method of high-precision femtosecond laser beam shaping

2.1. Keplerian dispersion compensation module

The KDCM is a Keplerian telescope system consisting of two groups of positive lenses, as shown in figure 1(a). Its angular magnification is

$$M = \frac{f_{front}(\lambda)}{f_{rear}(\lambda)} = \frac{M_0 \lambda_0}{\lambda} \quad (1)$$

where f_{front} denotes the focal length of the front lens group (FLG); f_{rear} denotes the focal length of the rear lens group (RLG); λ_0 denotes the center wavelength of the KDCM, and M_0 denotes the angular magnification of the KDCM at the center wavelength. The KDCM is a Keplerian telescope system, and also is a 4-*f* configuration. The DMD is placed in the front focal plane of the KDCM, and the optical axis of KDCM coincides with the direction of non-dispersion of the DMD.

2.2. Schematic diagram of the system

The schematic diagram of the system of high-precision femtosecond laser beam shaping is shown in figure 1(b). The pulse laser is produced by a Ti: sapphire femtosecond laser, passing through a grating and then imaged to the DMD. The femtosecond laser is Chameleon Ultra II, Coherent, USA; the grating is GR25-0610, blaze angle is 17°27', 600 lines/mm, Thorlabs, USA; the DMD is 1024 × 768 pixels, DLP7000, Texas Instruments, USA. By means of programming the hologram on DMD, the femtosecond laser beam can be modulated to arbitrary amplitude and phase. Due to the inherent grid structure of the DMD, it is actually a blazed grating and will introduce angular dispersion resulting in deterioration of the femtosecond laser beam. We use a grating and a 4 - *f* configuration to pre-compensate the dispersion introduced by the grid structure of the DMD, and a Keplerian dispersion compensation module (KDCM) to compensate the dispersion introduced by the hologram loaded on the DMD.

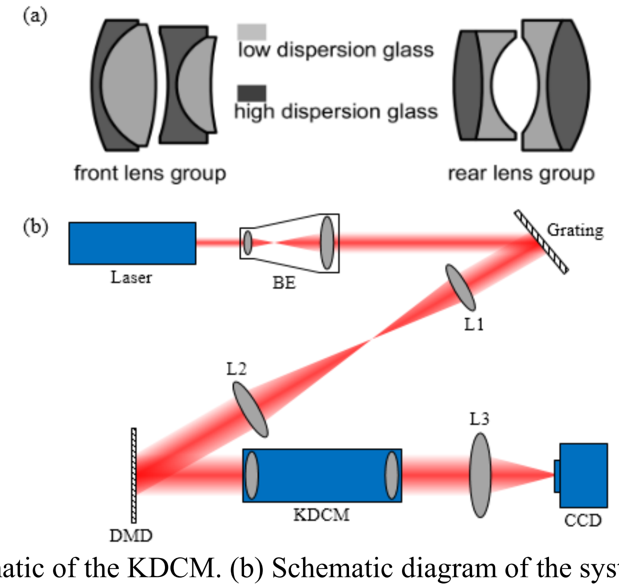

Figure 1. (a) Schematic of the KDCM. (b) Schematic diagram of the system of high-precision femtosecond laser beam shaping. Laser: Ti: sapphire femtosecond laser; BE: beam expander; KDCM: Keplerian dispersion compensation module; L1, L2, and L3: lenses.

3. Results and discussion

3.1. Beam shaping of points

Figure 2 shows the result of scanning the beam via the DMD from -1° to 1°. We programmed the DMD to deflect the beam and captured 25 pictures distributing uniformly in the field of view. As

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shown in figure 2, when the beam pass through the DMD, it will introduce dispersion resulting in the beam stretched. The grating can compensate the dispersion under a specific condition, as show in the red box in figure 2(a). However, in the other field of view, the dispersion still exists, lead to the worse quality of the beam. As shown in the magenta box in figure 2(a), the light spot is stretched. Figure 2(b) shows the light spots after the beam passing through KDCM. We can see clearly that the light spot is very uniform in the whole field of view. Two areas are selected to compare with the light spot without KDCM, the green box and the blue box in figure 2(b). Figure 2(c) shows the cross-section of the spots in figure 2(a) and figure 2(b). The spot is widened in one dimension but recovered to a circle spot after KDCM. The black curve represents the theoretical value. It is observed that the light spot is near diffraction limit in the whole field of view with the KDCM.

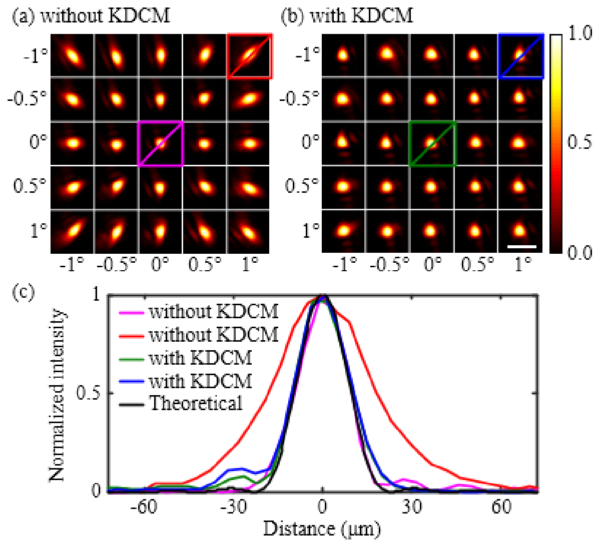

Figure 2. (a) Light spots deflected from -1° to 1° without KDCM and (b) is with KDCM; (c) Intensity of the oblique coloured lines in figure 2(a) and 2(b); the black curve represents the theoretical value.

3.2. Beam shaping of arbitrary pattern

Next, we demonstrate the ability of high-precision arbitrary beam shaping based on the system in figure 1(b). The DMD is loaded a hologram via Lee holography[9] and Gerchberg–Saxton algorithm[10] to generate a beam of arbitrary shape. First, the laser beam is shaped into a pattern of decorated letter of 'HUST' as shown in figure 3(a) with the KDCM, and figure 3(b) without the KDCM. Attention the cyan arrows in figure 3(a) and figure 3(b), it is obvious that without the KDCM, the pattern is blurred and indistinct, especially in the place has complex pattern. That is because dispersion introduced by the DMD stretching the beam. According to the angular spectrum theory, the pattern generated by hologram can be decomposed into as all kinds of frequency. The grating we used to compensate the dispersion is at a specific frequency. The beam at other frequency still exists dispersion. The KDCM can solve this problem well. As shown in figure 3(b), the pattern 'HUST' become clear and distinct in detail with the KDCM. Then, we generated a series of concentric annuli via DMD to demonstrate this issue better, as shown in figure 3(c), without the KDCM, and figure 3(d), with the KDCM. Intuitively, the annuli in figure 3(d) is distinguishable but indistinguishable in figure 3(c). Obviously, there are 6 annuli in figure 3(d). Figure 3(e) is the intensity projection along the vertical direction in the magenta box in figure 3(c) and the green box in figure 3(d). We can count 6 peaks of wave, representing the 6 annuli, according to the green curve.

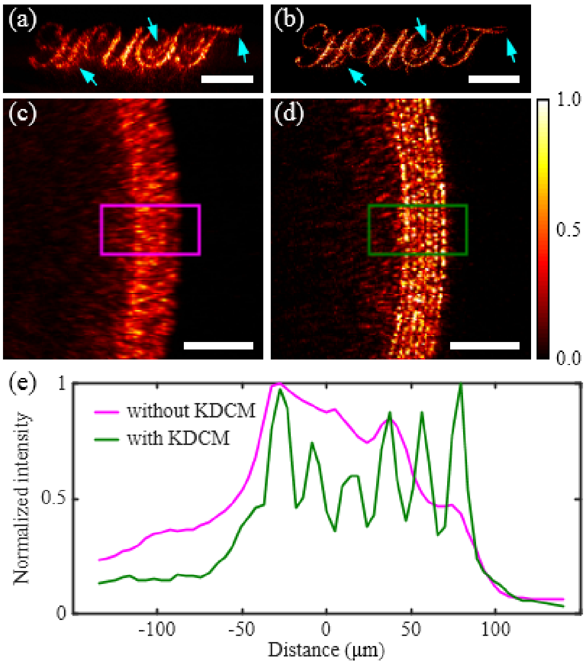

Figure 3. (a) and (b) is the pattern of decorated letter of 'HUST' without KDCM and with KDCM respectively; (c) and (d) is the pattern of a series of concentric annuli without KDCM and with KDCM respectively; (e) intensity projection along the vertical direction in the magenta box in figure 3(c) and the green box in figure 3(d).

4. Conclusion

In conclusion, we have proposed a method of high-precision femtosecond laser beam shaping via digital holography. The light spots approaching diffraction limit in the whole FOV can be achieved, and the result of the pattern 'HUST' and concentric annuli confirms that we have the ability of shaping the beam into arbitrary intensity profile. Furthermore, this method can be used to any DOE, not just DMD. If we don't need to shape the beam so fast, we can use the SLM to replace the DMD to achieve more application.

Acknowledgments

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References

[1] Nolte S., Momma C., Kamlage G., Ostendorf A., Fallnich C., von Alvensleben F., Welling H. (1999) Polarization effects in ultrashort-pulse laser drilling. Applied Physics A, 68: 563–567.
[2] Niziev V. G., Nesterov A. V. (1999) Influence of beam polarization on laser cutting efficiency. Journal of Physics D: Applied Physics, 32: 1455-1461.
[3] Steen W., Mazumder J. (2010) Laser Welding. In: Laser Material Processing. Springer, London. 199-249.
[4] Zhang Y.L., Chen Q.D., Xia H., Sun H.B. (2010) Designable 3D nanofabrication by femtosecond laser direct writing. Nanotoday, 5: 435-448.
[5] Fatemi F. K., Bashkansky M. (2006) Generation of hollow beams by using a binary spatial light modulator. Optics Letters, 31: 864-866.
[6] Cheng J., Gu C., Zhang D., Chen S.C. (2015) High-speed femtosecond laser beam shaping based on binary holography using a digital micromirror device. Optics Letters, 40: 4875-4878.

IOP Conf. Series: Materials Science and Engineering **569** (2019) 022026 doi:10.1088/1757-899X/569/2/022026

[7] Li D., Zeng S., Lv X., Liu J., Du R., Jiang R., Chen W. R., Luo Q. (2007) Dispersion characteristics of acousto-optic deflector for scanning Gaussian laser beam of femtosecond pulses. Optics Express, 15: 4726-4734.
[8] Geng Q., Gu C., Cheng J., Chen S.C. (2017) Digital micromirror device-based two-photon microscopy for three-dimensional and random-access imaging. Optica, 4: 674-677.
[9] Lee W.H. (1974) Binary Synthetic Holograms. Applied Optics, 13: 1677-1682.
[10] Gerchberg R. W., Saxton W. O. (1972) A practical algorithm for the determination of phase from image and diffraction plane pictures. Optik, 35: 237-250.