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Holographic femtosecond laser processing

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Holographic femtosecond laser processing performs an arbitrary and variable parallel patterning by use of a computer-generated hologram displayed on a liquid crystal spatial light modulator.

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Abstract

Parallel femtosecond laser processing using a computer-generated hologram (CGH) displayed on a liquid crystal spatial light modulator (LCSLM) is demonstrated. The use of the LCSLM enables to perform an arbitrary and variable patterning. This holographic femtosecond laser processing has advantages of high throughput and high light-use efficiency. A critical issue is to precisely control the intensities of the diffraction peaks of the CGH. We demonstrate some methods for the control of the diffraction peaks. We also demonstrate the laser processing with two-dimensional and three-dimensional parallelism.

1. Introduction

Femtosecond laser processing inside transparent materials has advantages of high spatial resolution due to multi-photon absorption and reduced thermal destruction of the target due to the extremely short pulse duration. Therefore, the femtosecond laser processing has been used to develop three-dimensional (3-D) optical devices. To fabricate the 3-D optical devices composed of a huge number of processing points, parallel femtosecond laser processing with high throughput is indispensable.

Holography gives the features of high throughput, high light efficiency, and material-dependent light distribution ser to the femtosecond laser processing.[1-5] Especially, computer-generated holograms (CGHs) are very useful and powerful tool, because the CGH can generate a desired arbitrary beam, such as a spatially-shaped beam, a split beam, a focused beam, and a wave-front corrected beam, with low loss of light. The CGH is variably displayed on a liquid-crystal spatial light modulator (LCSLM). A key requirement in the design of the CGH is a precise control of the diffraction peak intensity. A lot of methods for the control have been applied.

In this paper, we demonstrate holographic femtosecond laser processing with two- and three-dimensional parallelism. The Fourier CGH is designed by the optimal-rotation-angle (ORA) method with compensation of the spatial frequency response of the LCSLM.[4] The Fresnel CGH is the multiple phase Fresnel lenses (MPFL)[2,3] with high uniformity of the diffraction intensities, mainly described in this paper.

2. Experimental setup

Figure 1 shows the holographic femtosecond laser processing system. The system mainly consists of an amplified femtosecond laser system and an LCSLM. The laser system generates pulses with a center wavelength of 800 nm and a pulse width of ~150 fs. The pulse energy is adjusted with a set of neutral density filters before being collimated by a beam expanding optics. The pulse is irradiated to the LCSLM. The LCSLM forms a spatial refractive index change by the image signal from the computer. The refractive index changes give the phase modulation to the irradiation pulse. The pulse is diffracted by the MPFL formed on the LCSLM and forms a desired pattern on the sample through a reduction optical system composed of lenses and a 60× objective lens (OL) with a numerical aperture (NA) of 0.85. A charge coupled device (CCD) image sensor, a dichroic mirror (DM), a filter, and a halogen lamp (HL) are used to observe the processing.

Observation of the processed area is performed by optical microscope with transmitted illumination. An atomic force microscope (AFM) and a scanning electron microscope (SEM) are also used to measure the nanometer-scale structure of the processed area.

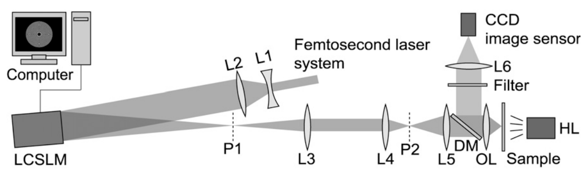

Fig. 1 Holographic femtosecond laser processing system.

3. Experimental results

Figure 2 shows the experimental results of the holographic femtosecond laser processing. Figure 2(a) shows an original MPFL, which has a constant initial center phase of $\phi_n = 0$ radian without the optimization. Figure 2(b) shows the computer reconstruction of diffraction pattern and its intensity profile. The uniformity U was 78%. The uniformity is defined as $U = I_{min}/I_{max}$, where I_{min} and I_{max} are the minimum and the maximum peak intensities, respectively. Figure 2(c) shows the optical reconstruction observed at P1 and its

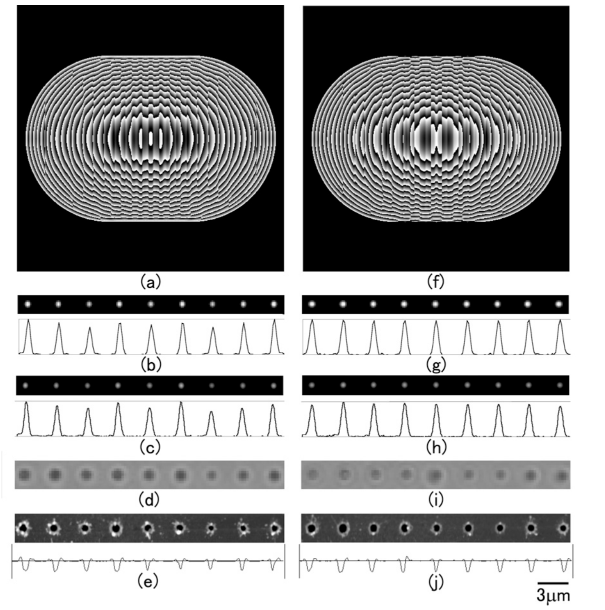

Fig. 2 (a) Non-optimized MPFL, (f) optimized MPFL. (b), (g) computer and (c), (h) optical reconstructions. (d), (i) Optical microscope observation, (e), (j) AFM observation of the fabricated area.

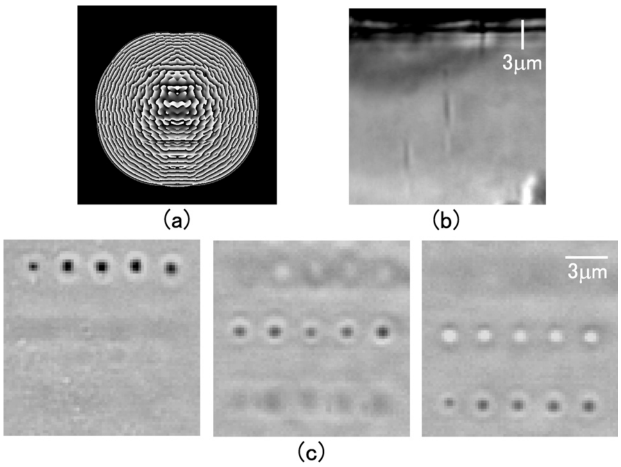

Fig. 3 (a) CGH for single-shot 3D processing. (b) Side view and (c) top views of the fabricate area.

intensity profile. U was 73%. Figures 2(d) and 2(e) show a transmission microscope image and an AFM image of the fabricated area processed with the energy of 2.4 μJ, respectively. The pits had a minimum diameter d_{min} of 477 nm and a maximum diameter d_{max} of 793 nm. The pit diameter was measured as the distance between two zero-crossing points near the pit center in the AFM profile. The uniformity of the pit diameter, $U_d = d_{min}/d_{max}$, was 60%.

Figure 2(f) shows a MPFL that is optimized by changing the initial phase of the each PFL. Figures 2(g) and 2(h) show the computer and optical reconstructions, respectively. U were 97% and 88%, respectively. Figures 2(i), and 2(j) show the transmission microscope image and the AFM image, respectively. d_{min} was 628 nm and d_{max} was 783 nm. U_d was 80%. The regulation of the center phases makes a MPFL with higher quality.

Figure 3 shows the 3D parallel laser processing with a single pulse irradiation. Figure 3(a) shows an MPFL formed of the 15 multiplexed PFLs, which have focal lengths of 900, 1148, and 1243 mm. The focus positions were on the glass surface, at a 15μm depth, and at a 20μm depth inside the glass, respectively. Figures 3(b) and 3(c) show the side and the axial views of the transmission microscope images.

4. Conclusions

We have demonstrated the holographic femtosecond laser processing with an MPFL, which was optimized by regulating the center phase of the constituent PFLs while taking account of the LCSLM properties and the spatial profile of the irradiated laser pulse. By these optimizations, the uniformity of the diffraction peaks was improved. We have demonstrated the 2D and 3D parallel femtosecond laser processing with single-pulse irradiation. Recently, we have demonstrated MPFL with higher quality by optimizing the diameter and phase range of each PFL. This technology is useful to fabricate 3D microstructures inside the material and arbitrary-shaped material surface.

Acknowledgments

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