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Controllable grating fabrication by three interfering replicas of single femtosecond laser pulse*

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The controllable periodic M-shape gratings are fabricated on the surface of silica glass by three coplanar interfering beams from a single femtosecond pulse. The configuration of the M-shape periodic structure is characterized by optical microscopy and atomic force microscopy. The experimental results and the theoretical simulation show that the period and the modulation depth ratio between the neighboring grooves of the fabricated gratings can be controlled by adjusting the collision angles and pulse energy of the three beams, respectively.

Keywords: multi-beam interference, M-shape grating, multi-photon ionization

PACC: 4225G, 4240E

1. Introduction

Multi-beam interference based on a femtosecond laser micro-fabrication technique has become one of the most promising and efficient ways to fabricate periodic micro and nano-structures because this technique does not need such expensive fabrication systems as focused ion beam (FIB)[1] and electrons beam lithography (EBL).[2] Two-beam interference can induce one and two-dimensional periodic structures by single and double-exposure techniques, respectively,[3−7] However, usually the second pulse could not overlap completely with the microstructure formed by the first pulse in the double-exposure technique due to the rather small size of the focal spot, and therefore its application to the fabrication of periodic photonic crystal structures is severely hindered.

Recently, many researchers have employed a multi-beam interference method to fabricate periodic structures with using several beam splitters[7−9] and a diffractive beam splitter (DBS),[10−13] which can achieve the better formation of two-dimensional and three-dimensional periodic microstructures. In the above-mentioned methods, the DBS method is easy to achieve the temporal overlap of interfering beams, for there is no need to adjust the optical path length. But the pulse energy is limited by the diffraction efficiency, so it is very difficult to fabricate period structures on wide bandgap materials by the DBS method, such as silica glass. Moreover, the collision angles of the incident beams for the DBS method are too small to obtain the microstructures with a smaller period. In contrast, the beam-splitter method has extreme predominance in changing the energies and the collision angles of the interfering beams, though the precise adjustment of the optical path is rather difficult. This technique allows the periodic microstructure to be encoded on almost all kinds of materials, including the glasses, metals, photosensitivity materials, and so on. Based on the above comparison, we adopt beam splitter method according to our experiment condition.

In our previous studies, Guo *et al*[14] have fabricated modulation gratings by two interfering femtosecond laser pulses on the surface of the silica glass. The modulation grooves are formed, owing to second-harmonic generation (SHG) effect, so it is difficult to control the modulation depth ratio of the neighbouring grooves. In the present paper, we report on the fabrication of M-shape gratings with controllable modulation depth by adding the third beam into a two-beam interference. The experimental results show that the depth ratio between neighbour grooves can be conveniently controlled by changing the pulse energy of the third beam. Morphology characterizations of as-fabricated periodic M-shape gratings with a period of ~ 2.6 μm are presented by optical microscopy and atomic force microscopy (AFM). A theoretical simulation well fits the experimental results.

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2. Experiment

The schematic experimental setup for fabricating M-shape grating is shown in Fig.1. The ultrafast pulses (with a pulse width of 120 fs, central wavelength of 800 nm, and repetition rate of 1–1000 Hz) used in our experiments are produced by a Ti:sapphire regenerative amplified laser system (Coherent Inc). A laser pulse with a diameter of $\sim$ 5 mm is split into three beams by two beam-splitters. Then three beams are focused by three lenses (L_1, L_2, and L_3), each with a focal length of 150 mm, to give a spot size of $\sim$ 50 μm at the focal plane. The collision angles between L_1–L_2, L_2–L_3, and L_1–L_3 are θ, θ, and 2θ ($\theta = 18^\circ$ and 30° in our experiments), respectively. Two time-delay devices are employed for time adjustment of the beams collision. A BBO frequency-double crystal is located at the focal spot to check time superposition by SHG. When three collinear blue points appear on the white screen located on the back of frequency-double crystal, it indicates that three beams have been superposed on each other both spatially and temporarily. Two attenuators are used to adjust the energy of femtosecond laser pulse. The sample silica glass available from Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences is located in the direction perpendicular to beam L_2. The panorama and the three-dimensional morphology of as-fabricated periodic M-shape grating are characterized by optical microscope (Nikon Inc.) and AFM (Nano Scope IIIa, Digital Instruments), respectively.

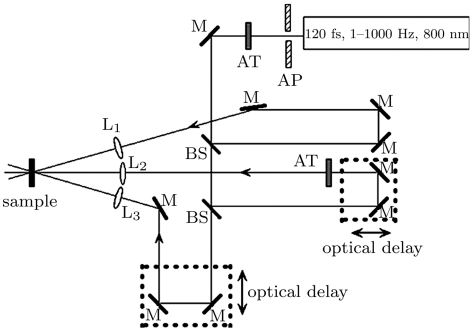


Fig.1. Experimental setup of three-beam interference optical system (AT and AP stand for attenuator and aperture, respectively).

3. Results and discussion

The optical microscope images of the gratings formed on the silica glass at different pulse energies of L_2 ($\theta = 18^\circ$, the pulse energies of L_1 and L_3 are both 50 μJ) are shown in Figs.2(a) and 2(b). The periodic gratings are formed in circular zones with diameters of $\sim$30 μm and $\sim$40 μm, respectively. From Fig.2(a) we can see that the neighbouring grooves with different widths alternatively appear in the grating. However, in Fig.2(b), the neighbouring grooves of the as-formed grating have the same widths.

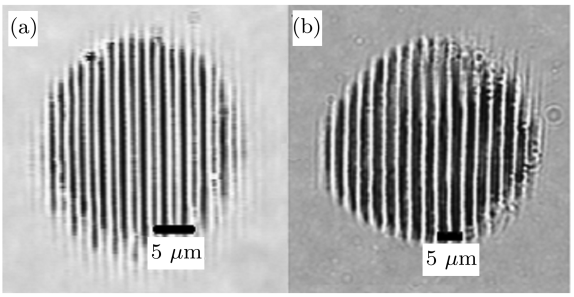


Fig.2. Optical microscope images of as-formed gratings by coplanar three-beam interference with different pulse energies of L_2, i.e. (a) 50 μJ and (b) 100 μJ.

Figure 3 shows the AFM characteristic results of as-formed grating (in Fig.2(a)). Figure 3(a) is a top-view AFM image of the grating, where the neighbouring grooves with different widths alternately appear more clearly. Figure 3(b) displays the three-dimensional morphology, which clearly shows that the M-shape grating is formed by the alternate appearing of two kinds of grooves: the deeper grooves and the shallower grooves. Figure 3(c) indicates a cross-section scanning picture along the horizontal line 'L' shown in Fig.3(a). It is obviously shown that the structure is formed by periodically arranging the M-shape units with a size of about 2.6 μm. The modulation depths of the deeper grooves and shallower

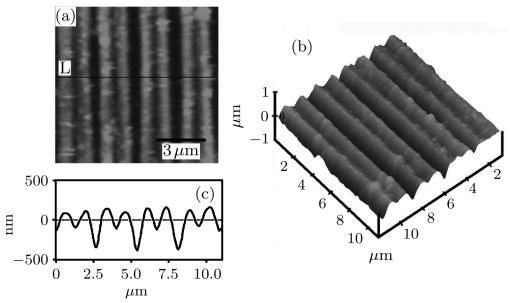


Fig.3. AFM images of the M-shape grating formed on silica glass by three coplanar interfering beams, each with equal energy of 50 μJ, the collision angles of three beams are 18°, 18°, and 36°, respectively. Panel (a) is for planar image, panel (b) for three-dimensional image, and panel (c) for cross-section pattern along line L.

grooves of the M-shape grating are $\sim$500 nm and $\sim$240 nm, respectively. The deeper grooves and the shallower grooves of the M-shape grating each have a

period of ∼2.6 μm revealed in Fig.3(c). This result accords well with the value calculated from the universally known period formula $d = \lambda/\sin\theta$ (in our case $\lambda = 800$ nm, $\theta = 18°$, and $d \approx 2.59$ μm).

In order to control the period and the modulation depth of the grating by tuning collision angle and pulse energy, we conduct the following experiments. When we increase the collision angle θ from 18° to 30° and keep the energy at 50 μJ, the period decreases from ∼2.6 μm to ∼1.6 μm. The modulation depth is accordingly reduced to ∼240 nm for deeper grooves and ∼80 nm for shallower grooves. When we increase the energy of L_2 from 50 μJ to 100 μJ and keep other parameters unchanged, the M-shape grating changes to the ordinary grating with a period of ∼2.6 μm without M-shape as shown in Fig.2(b). It indicates that the modulation depth of the M-shape grating increases with the laser pulse energy increasing, but decreases with the increase of colliding angles of three coplanar interfering beams. Nevertheless, the period increases only when the colliding angle decreases. Moreover, it should be pointed out that the depth ratio of the deeper grooves and the shallower grooves of the M-shape grating can be controlled by changing the pulse energy ratio of three interfering beams.

Then we will discuss the controlling of M-shape gratings in theory. As demonstrated in our experiments, the depth ratio of the neighbouring grooves is mainly related to the energy ratio of the incident pulses, though it can also be changed by the collision angle. In order to study the dependence of modulation depth ratio of neighbouring grooves on the energy ratio of the three pulses, the following discussion is preformed under certain collision angles ($\theta = 18°$).

The spatial intensity distribution in the interference region of three laser beams can be expressed as follows:[9]

$$I = \sum_i I_{0i} + 2\sum_{i<j} \sqrt{I_{0i} I_{0j}} \cos\gamma_{ij} \cos\delta_{ij}, \quad (1)$$

and

$$\delta_{ij} = (\boldsymbol{k}_i \cdot \boldsymbol{r}_i - \boldsymbol{k}_j \cdot \boldsymbol{r}_j) + \Delta\varphi_{ij} (i, j = 1, 2, 3), \quad (2)$$

where I_{0i} and I_{0j} are the intensities of the i-th and j-th plane-waves; γ_{ij} is the angle between the linearly polarized directions of the i-th and j-th waves; δ_{ij} and $\Delta\varphi_{ij}$ are the total phase difference and initial phase difference of the i-th and j-th waves, respectively; $\boldsymbol{k}$ is the wave vector; $\boldsymbol{r}$ is the position vector. The physical parameters used in our simulation are shown in Table 1, where $k = 2\pi/\lambda$, $\lambda = 800$ nm, and $\theta = 18°$. In the simulation, we just change the energy of the middle beam (L_2) from 20 μJ, to 50 μJ and 100 μJ, and keep the energy of other two beams at 50 μJ. The pulse energies of L_1, L_2, and L_3 are respectively transformed to spatial intensities I_{01}, I_{02}, and I_{03} as listed in Table 1. The relation $\gamma_{12} = \gamma_{13} = \gamma_{23} = 0$ is employed, for three beams have the same linearly polarized directions. Moreover, for the interfering laser, the initial phase difference $\Delta\varphi_{ij}$ is a constant, which is reasonably set to be zero for more convenient calculation ($\varphi_{12} = \varphi_{13} = \varphi_{23} = 0$). The total phase difference in xoy-plane are $\delta_{12} = kx\sin\theta$, $\delta_{13} = 2kx\sin\theta$, and $\delta_{23} = kx\sin\theta$ according to Eq.(2).

Table 1. Physical parameters used in simulation.

$I(\times 10^{13}$ W/cm$^2)$			γ			δ			$\Delta\varphi$		
I_{01}	I_{02}	I_{03}	γ_{12}	γ_{13}	γ_{23}	δ_{12}	δ_{13}	δ_{23}	$\Delta\varphi_{12}$	$\Delta\varphi_{13}$	$\Delta\varphi_{23}$
2.12	0.85	2.12									
2.12	2.12	2.12	0	0	0	$kx\sin\theta$	$2kx\sin\theta$	$kx\sin\theta$	0	0	0
2.12	4.24	2.12									

The simulated intensity distributions in the interfering region formed by three coplanar interfering beams are shown in Figs.4(a), 4(b) and 4(c), which correspond to the middle beam (L_2) pulse energies of 20 μJ, 50 μJ and 100 μJ, respectively. In Figs.4(a), 4(b) and 4(c), the upper images show the three-dimensional patterns and the nether curves display the two-dimensional cross-section patterns. From the cross-section images of Figs.4(a), 4(b) and 4(c) we can see clearly that the periodic intensity patterns are formed by the periodic arrangement of inversely M-shape structures, which is attributed to stronger intensity peaks and weaker ones arrayed with the same period of about 2.6 μm alternately and periodically. These results are consistent with the AFM results as

shown in Fig.3. We notice that with the energy of the middle pulses increasing, the stronger intensity peaks in the interfering region increase, while the weaker intensity peaks decrease. It indicates that the intensity ratio of the stronger peak and the weaker one increases. If laser pulses with such a periodic inversely M-shape intensity distribution irradiate the materials, the stronger intensity peaks will lead to the formation of deeper grooves, and the weaker intensity peaks will induce the formation of shallower ones. As a result, the M-shape surface structures will be resultantly formed.

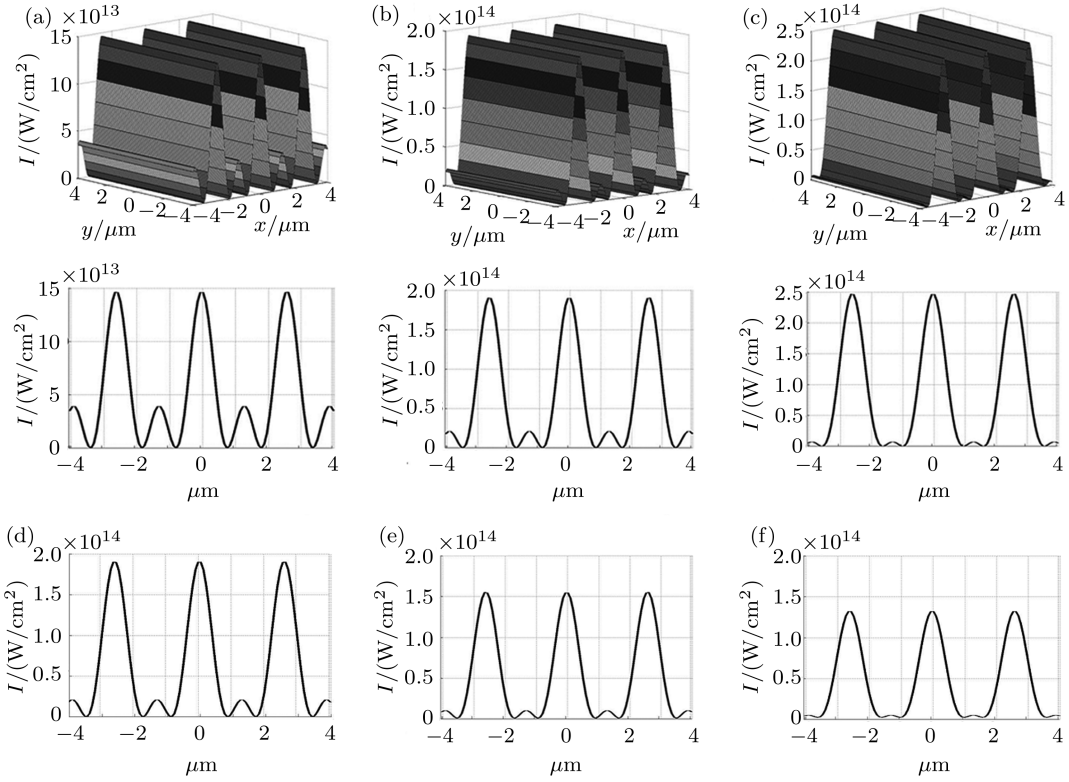


Fig.4. Intensity distributions simulated by using three interfering coplanar beams with different pulse energies of L_2 (4(a), 4(b), and 4(c)) and L_3 (4(d), 4(e), and 4(f)), where $k = 2\pi/\lambda$, $\lambda = 800$ nm, $\theta = 18^\circ$ and different values of I_{01}, I_{02} and I_{03}, i.e. (a) $I_{01} = 2.12$, $I_{02} = 0.85$, and $I_{03} = 2.12$, (b) $I_{01} = 2.12$, $I_{02} = 2.12$, and $I_{03} = 2.12$, (c) $I_{01} = 2.12$, $I_{02} = 4.24$, and $I_{03} = 2.12$, (d) $I_{01} = 2.12$, $I_{02} = 2.12$, and $I_{03} = 2.12$, (e) $I_{01} = 2.12$, $I_{02} = 2.12$, and $I_{03} = 1.06$, and (f) $I_{01} = 2.12$, $I_{02} = 2.12$, and $I_{03} = 0.53$, which are all in units of 10^{13} W/cm^2.

In simulation, the physical parameters used in Figs.4(b) and 4(c) are consistent with those of our experimental conditions. From Fig.4(b) we can see that the intensity to form the deeper grooves is nine times larger than that to form the shallower grooves according to the formula given above. But actually the modulation depth of the deeper grooves of the M-shape grating is only about twice larger than that of the shallower grooves, as calculated from the AFM data. It suggests that the modulation depth is not proportional to the interference intensity, which could be explained by the interaction process of femtosecond laser with materials. In our experiment, the maximum intensity in the interfering region can reach the values of up to more than 100 TW/cm^2. In such a high intensity, the silica glass is ionized very rapidly by combined actions of multi-photon ionization and avalanche ionization, and a layer of the critical-density plasma is generated after the anterior part of the incident pulse impacts on the surface of the silica glass.[15] Because of the ultrafast characteristic of the femtosecond laser pulse, the duration is too short for the substantial expansion of the plasma layer to take place. So the as-formed dense plasma is confined in the thin surface layer. The dense plasma would strongly reflect the subsequent part of the incident pulse, which weakens the energy of the subsequent pulse and holds back the further interaction between the femtosecond laser pulse and the bulk material.[15−17] Moreover, for higher laser intensities, the strong reflection will occur

in the earlier stage of the incident pulse.[17] The above analyses suggest that the ablation will be confined in a thin substrate surface layer, and consequently the ablation depth will not accordingly increase with the increase of interference intensity remarkably.

In Fig.4(c), the weaker intensity peaks can still be observed, even though the intensity ratio of the two kinds of peaks becomes much large compared with those in Figs.4(a) and 4(b). But the shallower grooves are not formed under our experimental conditions (the energy of L_2 is 100 μJ and other parameters are kept unchanged) as shown in Fig.2(b), the formed structure is an ordinary grating without M-shape. This may be attributed to the weaker intensity peak in the interference zone lower than the threshold energy for the ablation of silica glass.[17]

In the present paper, we mainly study the controlling of M-shape grating by changing the energy of beam L_2. We can also modulate the M-shape grating by adjusting the pulse energies of beam L_1 and L_3. Figures 4(d), 4(e), and 4(f) show the simulation results, with the intensities of beams L_1 and L_2 kept at 2.12×10^{13} W/cm^2 but the intensity of beam L_3 decreasing from 2.12, 1.06 to 0.53×10^{13} W/cm^2. The results display that with the energy of beam L_3 decreasing, both the stronger and the weaker intensity peaks decrease as shown in Figs.4(d), 4(e), and 4(f). These results are different from the simulation results by changing the energy of beam L_2 as shown in Figs.4(a), 4(b) and 4(c). This means that the M-shape grating can be changed by adjusting the energies of the three beams.

4. Conclusions

We fabricated a controllable M-shape grating on the surface of silica glass by the interference of three coplanar replicas from a single femtosecond laser pulse. The modulation depth ratio of neighbouring grooves can be controlled by adjusting the energy ratio of the three beams. Our M-shape grating has potential applications in microfluidic chip devices as transport channels with different flowing speeds.

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