Fabrication of Dammann gratings in silica glass

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Dammann grating is one kind of binary optical elements. We fabricated Dammann gratings in silica glass using femtosecond laser pulses at the wavelength of 800 nm with the repetition rate of 1 kHz. By using two-dimensional (2D) scanning system, we produced successfully 5×5 Dammann gratings for He-Ne laser with the wavelength of 632.8 nm. We selected suitable writing parameters to keep the length of the refractive index changed region as 160 μm across the grating. It makes the phase shift of the modulated region close to be π. The diffraction efficiency of the fabricated Dammann grating in our experiment reached to 56%, quite close to the theoretical value of 77%.

OCIS codes: 050.1380, 050.2770, 220.4000, 230.3990, 230.4000, 320.0320.

Recently, femtosecond laser has been found as a powerful tool to produce optical micro-structures and devices in transparent materials. With the help of lens, femtosecond pulses are focused into a small region. The high peak power of the incident pulses around the focus makes nonlinear process occur in the media and introduce refractive-index change, even optical damages into transparent media. Nowadays, research works showed that waveguides[1,2], holes[3], gratings[4,5], Fresnel zone plates[6,7] and other types of optical micro-structures can be produced by femtosecond laser.

In optical micro-structures, the refractive index at certain region of the media is modulated. When light is incident into the devices, the phase distribution of the transmitted light varies from the original one. In the far field, we can realize different optical operations. For example, Dammann grating[8] is one typical kind of binary optical micro-structure. An N×M Dammann grating can convert an incident beam into two-dimensional (2D) array of N×M beams with the equal intensity. In Dammann grating, the uniform phase of the incident light is modulated into binary values, 0 and π, according to different applications. Nakaya *et al.* fabricated 6×6 Dammann gratings in silica glass by a femtosecond laser[9]. The diffraction efficiency of the grating was only 7.7%, only 11% of the theoretical efficient of their structure. They tried to write multi-layer and showed that the diffraction from 1×2 gratings can reach as high as 70%. Because of the complexity of the multi-layer writing, new simple method need be developed to produce Dammann gratings with high diffraction efficiently. In this paper, we produced Dammann grating in silica glass by using femtosecond laser. By careful selecting the writing parameters which made the phase change of the incident light close to the designed value, we produced Dammann gratings with quite high diffraction efficiently, 80% of the theoretical value.

In the experiment, a piece of silica glass with size of 3.0 × 5 .0 × 20.0 (mm) was used to write the Dammann grating. Femtosecond laser pulses from a Ti:sapphire amplifier working at the wavelength of 800 nm with the repetition rate of 1 kHz was used to write the optical micro-structure into the glass. The laser beam was focused into the glass by a microscopic objective (MDplan5×, NA=0.1, Olympus Corp.). The focal point was 500 μm below the glass surface. Here a 5×5 Dammann gratings designed for the wavelength of 632.8 nm. The outlook of one period of the 5×5 Dammann grating is shown in Fig. 1. The theoretical diffraction efficiency of the grating is 77.41%[10].

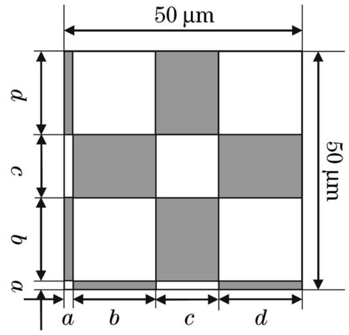

Fig. 1. The details of one period of the 5 × 5 Dammann grating. Here, a = 2.0 μm, b = 17.0 μm, c = 13.5 μm, and d = 17.5 μm, respectively.

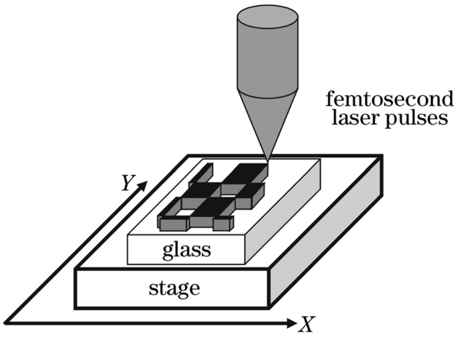

Fig. 2. Expeirmental setup. The femtosecond laser was focused into a piece of silica glass. By moving the stage, we make the focus scan across the sample to fabricate the Dammann grating.

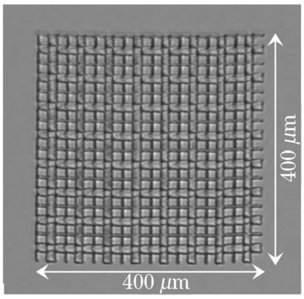

Fig. 3. Top view of the fabricated 5 × 5 Dammann Grating with 8×8 periods.

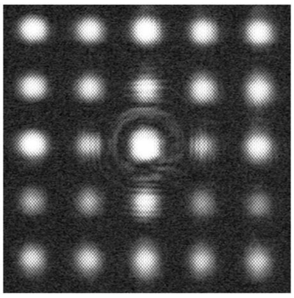

Fig. 4. The far-field fan-out pattern of He-Ne laser at 632.8 nm from the 5×5 Dammann grating with the periods of 8×8.

Obviously, the accurate location and the precise control of the refractive index modulation, i.e., the phase change of the transmitted light, are the two keys to produce micro-structure with high quality. In order to introduce optical damage at theoretical position, we fixed the glass on a computer-controlled 2D stage (V-102.2L, Physik Instrumente GmbH). By the 2D translation of the sample, the focus of laser beam scanned across the sample to write Dammann gratings. At first, we translated the sample along $x-$axis to write one line, and then shifted the sample along $y-$axis to write another line (see Fig. 2). The high accuracy of the stage made sure the exact location of the optical damage.

The diffraction efficiency of Dammann grating depends on two factors: the location of the phase modulated region and the phase modulation for the designed wavelength. In our experiment, phase change depends on the refractive index change of the glass introduce by the filament and the length of the refractive index change region. According to Ref.[5], the refractive-index change in silica glass using the filament was reported to be 2.0×10^{-3}. It means that if the length of the refractive index change region is 158 μm, the phase change will be π for light with the wavelength of 632.8 nm. The length of the change region depended on the incident energy per pulse, the scanning speed, the numerical aperture of the focusing lens, and other writing parameters. In our experiment by *in situ* monitoring system as the ones used in Ref. 2 and 5 we found that, when the incident energy was 1.0 μJ and the scanning speed along x-axis was 2.0 μm/s, the length of the refractive index changing region was approximately 160 μm. Using the above parameters, we tried to write Dammann grating.

We wrote 5×5 Dammann gratings with 2×2, 4×4, 6×6, and 8×8 periods. The total sizes of the gratings were 100 × 100 (μm), 200 × 200 (μm), 300 × 300 (μm), and 400 × 400 (μm), respectively. Figure 3 is the top-view of the Dammann grating with the period of 8×8. And we checked the fan-out effect of our gratings for the red He-Ne laser. Figure 4 shows the far-field fan-out pattern of red He-Ne laser from the Dammann grating with the periods of 8×8. The incident beam was split into 25 spots as expected. The diffraction efficiencies of Dammann gratings were 11.9%, 36.8%, 46.2%, and 55.8% for Dammann gratings with the periods of 2×2, 4×4, 6×6, and 8×8, respectively. The diffraction efficiency of the grating with the period of 8×8 closed to the designed value of 77.41%. The diffraction efficiency has no relationship with the polarization of the incident He-Ne beam. We measured the diffraction efficiency by varying the linear-polarization direction of the He-Ne laser beam with a half-wave plate. When the polarization direction of the linearly polarized He-Ne laser beam changed, the fan-out diffraction efficiency kept constant indicating that our Dammann gratings have no birefringence. This can be explained in fact that the refractive-index change in silica glass induced by filamentation within xy plane was anisotropic[12]. So in the application of our Dammann gratings, we need not take the polarization of the incident beam into account.

In conclusion, we fabricated the single layer birefringence-free Dammann gratings in silica glass by using a femtosecond laser. The diffraction efficiency of our grating reached 56%. With the accurate selection of the writing parameters, we introduce phase change of about π into the precise region of silica glass and made the fabricated Dammann grating have quite high diffraction efficiency 56%, 73% of the theoretical efficiency, in only one writing cycle. With the help of direct writing using the femtosecond laser, we can develop various types of the Dammann gratings with reasonable prices and superior qualities. In our experiment, the repetition of the laser is only 1 kHz, which make the writing time of the microstructure quite long. For the 8×8 grating it needed 24 hours. The long writing time made the filament formation unstable and decreased the quality of the grating. Using an amplified femtosecond laser with high repetition rate, for example, 200 kHz, will make it possible to fabricate Dammann gratings with higher diffraction efficiency and more uniform diffraction pattern. In the repetition rate of 200 kHz, the writing time is shorten than the case in our experiment (1 kHz), and the filament keeps high quality because no thermal accumulation occurs as the repetition rate is in MHz region[13,14].

This work was supported in part by the National Natural Science Foundation of China under Grant No. 60408006. Y. Li's email address is yudongli@nankai.edu.cn.

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