Fabrication of Dammann Gratings Inside Glasses by a Femtosecond Laser *

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Dammann grating is useful in information technology as an optical splitter. It is usually fabricated through complicated processes. Here we report on the direct fabrication of a 6×6 *Dammann grating in a silica glass by an 800 nm femtosecond laser. We also discuss the relationship between diffraction efficiency of* 1×2 *Dammann grating and laser irradiation conditions.*

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Ultrashort pulsed lasers have been used as a powerful tool to clarify elementary physico-chemical processes, such as excitation-energy relaxation and both electron and proton transfer on nanosecond and picosecond time scales, that occur in a micrometre-sized area.[1,2] Ultrashort lasers can also be used to make microscopic modifications to transparent materials. The reason for using these lasers is that its electric field intensity can reach 100 TW/cm^2, which is sufficient for inducing nonlinear optical effects in materials by using a focusing lens, when the pulse width is 100 fs and the pulse energy is 1 μJ. The photoinduced reaction is expected to occur only near the focused part of the laser beam due to nonlinear optical processes.

Up to now, there have been many studies on the microscopic modifications in transparent materials by using femtosecond lasers.[3] Various induced structures can be produced by using pulsed laser operating at the nonresonant wavelength with pulse widths in the order of femtosecond: coloured spot or line due to the formation of color centre, refractive index spot due to densification and defect formation, microvoid due to remelting and shock wave, microcrack due to destructive breakdown, etc.[4] Composite structures were also observed after focused femtosecond laser irradiation.[4] Promising applications using these phenomena have also been demonstrated for three-dimensional optical memory, photonic crystal, integrated optical circuit, and optical display.[3]

Dammann grating is one of the diffractive optical elements which can generate regular one- or two-dimensional beam patterns of equal intensity spots. Practically it is used as an optical splitter in information technology.[5] Other applications are for parallel digital optics, laser fabrication, etc.[6] The structure of Dammann gratings is designed under the condition that the intensity of each high-order diffractive light is equal to the intensity of the zero-order light.[7] Usually Dammann grating is fabricated through complicated processes, i.e. formation of a photoresist film on a glass substrate via spin coating, ultraviolet light exposure, etching, etc. All these processes take several days to be completed. Using the writing technique by the femtosecond laser, however, can shorten the processing time for fabrication of the Dammann grating. In this Letter, we report the fabrication of Dammann gratings in bulk silica glasses by a femtosecond laser. Moreover, we show that Dammann gratings with high diffraction efficiency can be obtained by a multilayer process.

The experimental setup consists of a regeneratively amplified Ti:sapphire laser delivering pulses of duration 150 fs with a maximum energy per pulse of 4 μJ at a repetition rate of 200 kHz. A glass sample was mounted on a three-dimensional translation stage, which was controlled by a computer. The glass sample was a 10 mm$\times$10 mm$\times$2 mm synthesized silica glass. The laser beam was focused inside the sample by a microscope objective. The average laser power was adjusted by an ND filter. The glass sample was translated perpendicular to the laser beam. The intensity distribution of the Dammann grating was measured by a powermeter (Newport, 2832-C) and detected by a CCD camera. Figure 1 shows a photograph of the microstructure of a 6×6 Dammann grating. The average power of the laser beam was 300 mW and a 20$\times$ objective lens with numerical aperture of 0.4 was used to focus the laser beam. The Dammann grating consists of many rectangle refractive index change patterns. In order to form a single rectangle pattern, several lines were written in specific pitch as shown in Fig. 1. The period was 250 μm both in the x and y axes. The

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period number was 16. Thus, the 2D size of the grating was 1 mm×1 mm. Figure 2 shows a diffraction pattern of the 6 × 6 Dammann grating. The light source was a He–Ne laser (633 nm). It is shown that the laser beam was split to 6 × 6 beams. Figures 3(a) and (b) show the intensity distribution of the split light along the line A–A′ and the line B–B′, respectively. The intensity distribution is quite uniform. The efficiency of the 6 × 6 Dammann grating is estimated to be 7.7%, which is smaller than the theoretical value of 71%.[8] This may be due to the small refractive index change and short length of the structure-modified region. We show that the diffraction efficiency can be improved by the way of a multilayer process.

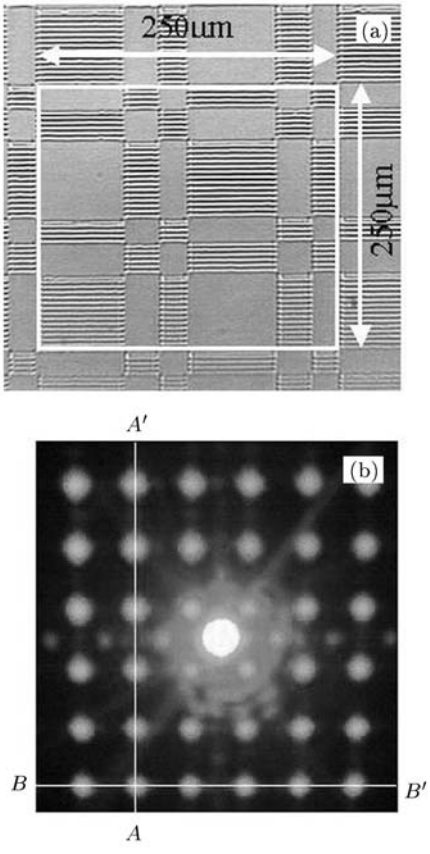

Fig. 1. Photograph of the microstructure (a) and diffraction pattern (b) of a 6 × 6 Dammann grating.

The phase shift ϕ of the input light passing through the grating is

$$\varphi = \frac{2\pi\Delta nL}{\lambda}, \tag{1}$$

where Δn is the refractive index change, L is the length of the refractive index change-region in the z direction, and λ is the wavelength of the input light. Generally, the diffraction efficiency η is proportional to $\sin^2(\phi/2)$. Thus, η is improved with the increase of ϕ when ϕ is smaller than π. There are two ways to increase ϕ. One is to make Δn as large as possible by adjusting the fabrication condition and the composition of the glass. The other is to make L much larger by piling another grating on the previous one, which is called a 'multilayer process'. We adopt the latter method and examine the diffraction efficiencies using basic 1 × 2 Dammann gratings.

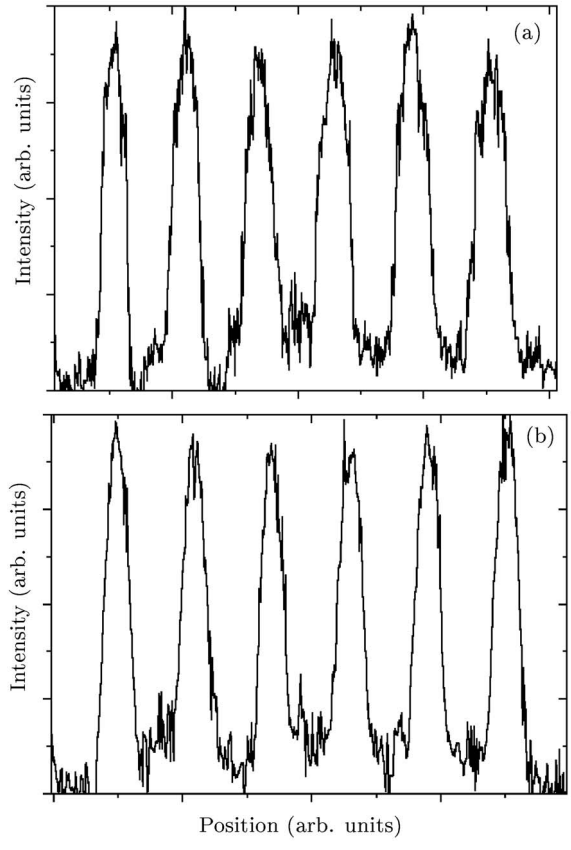

Fig. 2. Intensity distribution of split light along (a) the line A–A′ and (b) the line B–B′.

In this experiment, the average power of the laser beam was 240 mW. A 10× objective lens with numerical aperture of 0.3 was used to focus the laser beam. The translation speed of the stage was 25 mm/s. We fabricated 1 × 2 Dammann gratings that consisted of from single layer to four layers, and measured the diffraction efficiencies of each grating. The phase shift was calculated from the ratio of the high-order diffraction efficiencies. The least-squares method was used for the calculation. Figures 3 and 4 show the relation between the phase shift and the number of layers and the relation between the phase shift and the diffraction efficiency, respectively. Apparently the phase shift is proportional to the number of layers and the diffraction efficiency increases with an increase of the phase shift when the phase shift is smaller than p. However, the diffraction efficiency of the grating with four layers decreases because the phase shift becomes larger than p. The maximum diffraction efficiency of the multilayer grating reached 70%, which is comparable to the theoretical value of 81%.

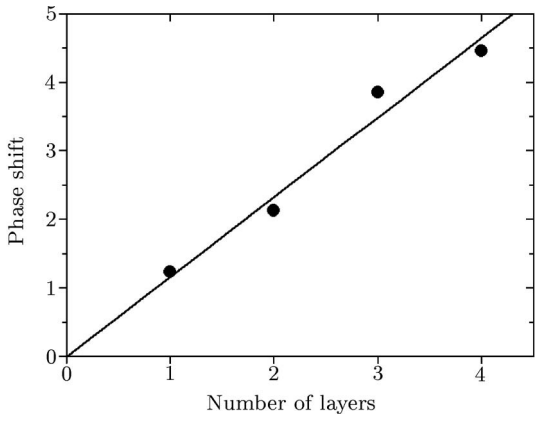

Fig. 3. Relation between the phase shift and the number of layers.

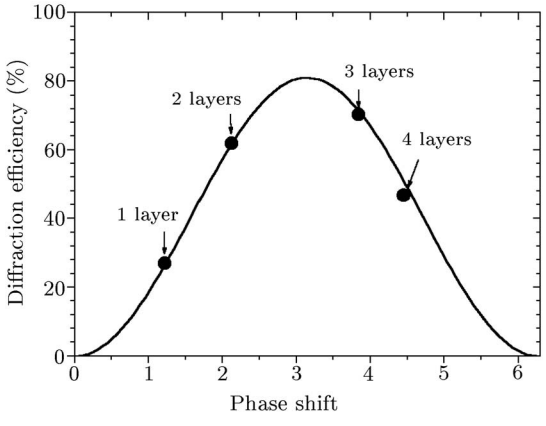

Fig. 4. Relation between the phase shift and the diffraction efficiency. The curve is $\eta = 8[\sin(\phi/2)/\pi]^2$, where η is the diffraction efficiency and ϕ is the phase shift.

In summary, we have fabricated the Dammann gratings by the 800 nm femtosecond laser. We have also demonstrated that the diffraction efficiency of the Dammann grating could be controlled through the multilayer process. It is easy to create three-dimensional structures in a glass by the femtosecond laser. Using this technique, we expect that novel optical components with composite functions can be developed.

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