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Characteristics of Filament Induced Dammann Gratings Fabricated Using Femtosecond Laser

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Abstract: To establish optimal processing conditions during direct write fabrication of diffractive optical elements such as gratings, waveguides, lenses, we have investigated the effect of process parameters such as scan speed, numerical aperture (NA) of objective lens, pulse energy on the characteristics of the filament induced inside fused silica with a femtosecond Ti:Sapphire laser. The optimum process parameters were used to fabricate a number of Dammann gratings, 6×6 array, having different thicknesses and number of layers. The performance of these optical elements was evaluated by measuring their diffraction efficiencies. The single layer Dammann grating fabricated with a thickness of 80 μm attained a maximum diffraction efficiency of 38.8 %.

OCIS codes: (050.1950) Diffraction gratings; (140.3390) Laser material processing

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1. Introduction

Femtosecond laser has been widely used in microscopic modifications of materials due to their ultra-short pulse durations which enable ultrahigh intensities. When a transparent material such as glass is irradiated by a tightly focused femtosecond laser beam below the surface, the photo-induced reaction occurs precisely around the focused spot-volume due to the characteristic multiphoton processes. This phenomena has attracted interest of both the scientific and technological communities since K. Miura [1] discovered that refractive index changes of the order from 10^{-2} to 10^{-3} can be induced within various types of glass. Since then, many research groups have demonstrated that localized structures can be induced inside the bulk glass using pulsed laser having pulse widths of the order of tens of femtoseconds. Effects such as color line due to the formation of color center and valence state change of active ions, refractive index change induced spot due to local densification and defect formation, micro-voids due to re-melting and shock wave, micro-cracks due to destructive breakdown etc. have been demonstrated [2]. The ability to induce spatially selective photo-induced refractive index changes in bulk glass makes it possible to directly write a variety of photonic devices, including waveguides [3], gratings [4], photonic crystals [5], directional couplers [6], three-dimensional binary data storage [7], and multicolor images [8]. Further, the integration of such optical elements and devices in monolithic glass blocks is expected to provide the flexibility, good mechanical stability and high integration density. One example of optical elements fabricated in this manner is a combination of diffractive lens and Dammann grating embedded in a single silica glass block.

The idea of using a computer-optimized binary phase grating as a beam splitter came from Dammann and Gortler in 1970 [9]; and since then, these holographic optical elements are often referred to as Dammann grating. Essentially, Dammann gratings are diffractive type gratings that generate arrays of uniform-intensity beams from an incoming beam of monochromatic light. They are particularly attractive for a variety of applications e.g. array illumination, multiple imaging in digital micro-optics, optical information processing, laser processing, etc [10]. A large number of these applications require an efficient use of the available light and therefore the grating is often chosen to be a phase grating rather than an amplitude grating. The two-level or binary-phase grating is the simplest type of grating to design and fabricate, requiring only a set of transition points and overall phase shift. In a binary phase grating, the grating pattern has two phase levels and a set of transition between the levels, the set including a plurality of periods of length p, where each period has a plurality of transitions between two levels. The two levels are separated by a phase depth equal to π. When a plane wave of light of wavelength λ which passed through a grating is focused by an objective lens of focal length f, N spots with equal spacing s are formed. The spacing between the N spots is given by

$$\text{Odd numbered spot array design: } s = f\frac{\lambda}{p} \tag{1-1}$$

$$\text{Even numbered spot array design: } s = 2f\frac{\lambda}{p} \tag{1-2}$$

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

$$\phi = 2\pi\Delta nL/\lambda \tag{2}$$

where Δn is the refractive index change, L is the thickness of layer with different refractive index and λ is the wavelength of the input light. In case of two phase level grating, efficiency η is given by

$$\eta = \sin^2(\phi/2)/(\phi/2) = \sin c^2(\phi/2) \tag{3}$$

Thus, η can be improved with an increase in ϕ and reaches its maximum when ϕ equals π. Primarily, there are two ways to increase ϕ. One way is to make Δn as large as possible and the other way is to make L longer either by multiple or single layer.

Fabrication of Dammann gratings inside bulk glass using a femtosecond laser was reported first by Nakaya et al. [4]. They fabricated a single-layer 6×6 grating with the overall dimension of 1 mm^2 inside fused silica substrate. The final measured diffraction efficiency in this case was 7.7%, which is far below the theoretical value of 71%. However, it was demonstrated that with simple 1×2 grating, the diffraction efficiency could be improved to the theoretical value by selecting the multilayer process. Recently, Li et al. [11] fabricated single-layer of 5×5 gratings using long filaments. The thickness of the grating was optimized to produce a phase shift of π. In this case, the diffraction efficiencies of Dammann gratings were shown to increase up to 55.8% with the increase in the number of periods up to eight.

In the present work, we report the direct write fabrication of Dammann gratings using filament induced by the femtosecond laser pulses along with a detailed study of parametric variations. In order to find the optimal processing conditions which resulted in the required length of the filament without defects, we first investigated the effects of pulse energy, scan speed and the numerical aperture of the microscope objective on the characteristics of the filaments induced inside the bulk fused silica glass. Based on the results obtained from optimal processing conditions, we fabricated a number of 6×6 Dammann gratings, having different thicknesses and periods inside bulk fused silica and examined the relationships between the process parameters with respect to the measured diffraction efficiency.

2. Experiment and discussion

2.1 Experimental set-up

In our experiment, a regeneratively amplified 775 nm Ti:Sapphire laser system (CPA-2010, Clark-MXR Inc.) with a pulse duration of 150 fs operating at 1 kHz repetition rate was used. The schematic of the experimental setup is shown in Fig. 1.

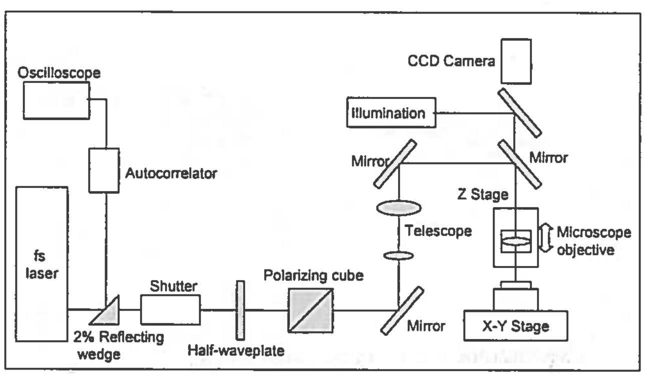

Fig. 1 Schematic diagram of the experimental setup

The original beam was passed through a circular aperture placed in front of the beam delivery system in order to improve the beam quality. The incoming laser beam had a Gaussian profile with a diameter of about 6 mm after magnifying 2 times using a beam expander. The laser beam was subsequently focused with a microscope objective lens (NA = 0.1, 0.2, 0.3) into the polished fused silica glass substrate (dimensions 3 × 25 × 25 mm) which was mounted on a computer controlled x-y translation stage having a resolution of 100 nm. The pulse energy was measured using a photodiode (Ophir, PD300-3W) that was placed after the microscope objective and varied between 0.3 and 4 μJ using a rotary half-wave plate and a linear polarizer. The glass sample was moved at a scan speed, ranging between 0.15 - 4 mm/min perpendicular to the incident beam.

2.2 Filamentation

To find out the characteristics of the filament induced by the femtosecond laser irradiation, the parameters such as the pulse energy, scan speed, and the numerical aperture of the microscope objective lens were selected. With the variation of these parameters, we machined rectangular patterns of ~40×100 μm^2 with the offset of 1 μm between the scan lines because single line of filament was hard to measure its shape accurately. As a result, a number of visible, grey color patterns inside the fused silica substrate were formed. The effect of pulse energy, translation speed and the numerical aperture of the microscope objective lens on the shape of the refractive index changed zone were investigated using a polarizing microscope.

The microscope images of the cross section of the rectangular patterns written at pulse energies of 0.3-3.7 μJ/pulse and scan speeds from 0.15-4.0 mm/min are shown in Fig. 2(a) and 2(b). It can be seen that the properties of the refractive index changed zone strongly depend upon the pulse energy, the scan speed, and the NA of the microscope objective lens. It was observed that the patterns induced with the lens having a NA = 0.1 appeared to be homogeneous, however, the geometrical thickness of the effected area was not uniform. In addition, the overall pattern shape was also trapezoidal with somewhat wider bottom. All of the patterns induced with the lens having a NA = 0.2 were homogenous, but they were discolored and became gradually darker in color with the increase in the scan speed, indicating effectively lesser change in the induced refractive index and stronger light scattering. The induced patterns with the lens having a NA = 0.3 showed the bulk ablation damage in the upper section of the pattern as shown in Fig. 2(a) when the scan speed was less than 0.3 mm/min. In case of NA = 0.3, there were conditions inducing a homogenous refractive index change without any damage, but the thickness of the refractive index changed zone was too small to induce a phase shift of π.

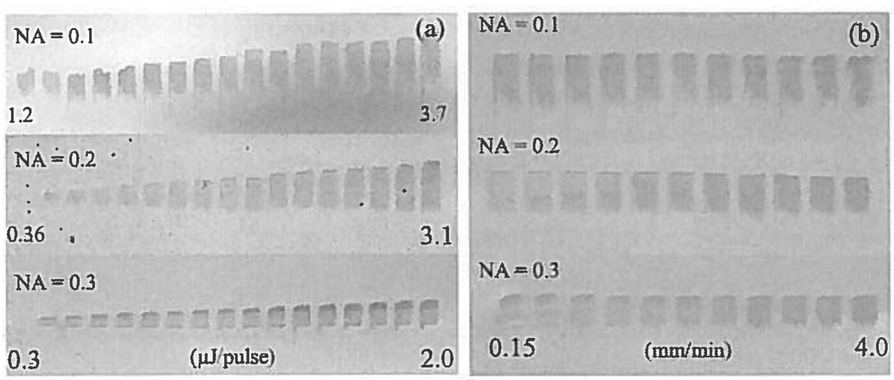

Fig. 2 Microscope photographs of the cross section of patterns written at various conditions; (a) pulse energy variation at scan speed of 0.3 mm/min, (b) scan speed variation at pulse energy of 2.6 μJ/pulse for NA = 0.1 and 1.4 μJ/pulse for NA = 0.2 and NA = 0.3

Fig. 3(a) and 3(b) indicate the variation of the thickness of the refractive index changed zone versus the pulse energy and scan speed. It was observed that the thickness increases with higher pulse energy and lower the value of NA, varied from about 20 μm to 130 μm, and slightly decreased with the increase in the scan speed. The measured width of the refractive index changed zone was varied from 41 to 43 μm with the increase in pulse energy, which means that the widths of the filament induced by single scan varied from 1 to 3 μm. Based on these experimental results, it was determined that the NA = 0.2 and the scan speed of 0.3 mm/min would provide the optimal processing conditions for the fabrication of Dammann gratings.

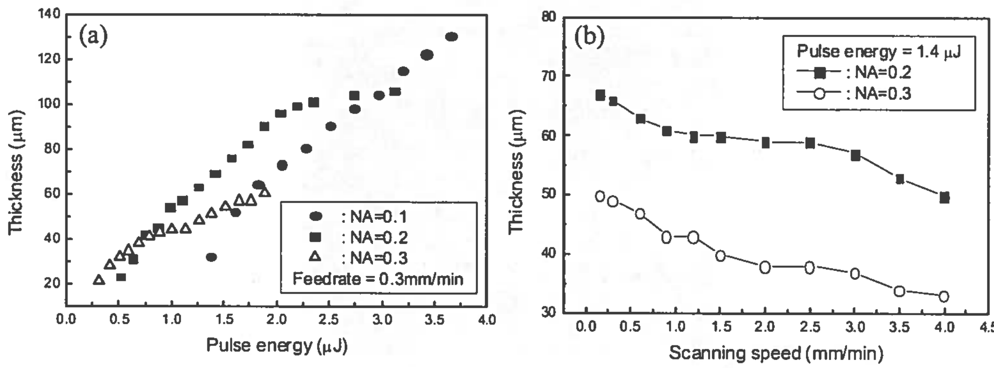

Fig. 3 Variation of the thickness of refractive index changed zone vs. process parameters; (a) Pulses energy, (b) Scan speed

2.3 Fabrication of Dammann gratings

The Dammann grating presented in this paper is based on separable, two dimensional (6×6) Dammann grating. The six transition points taken from Morrison [12] defined a grating to provide 6×6 spot array, with the theoretical diffraction efficiency of the grating in the order of 84.5%. At first, we fabricated gratings with the period p = 75 μm and 4×4 periods at various pulse energies to investigate the relationship between the diffraction efficiency and the grating thickness. Fig. 4(a) and 4(b) are the microscope photographs of the fabricated 6×6 Dammann grating, the magnified side view in Fig. 4(b) shows that its thickness is fairly uniform over the entire structure.

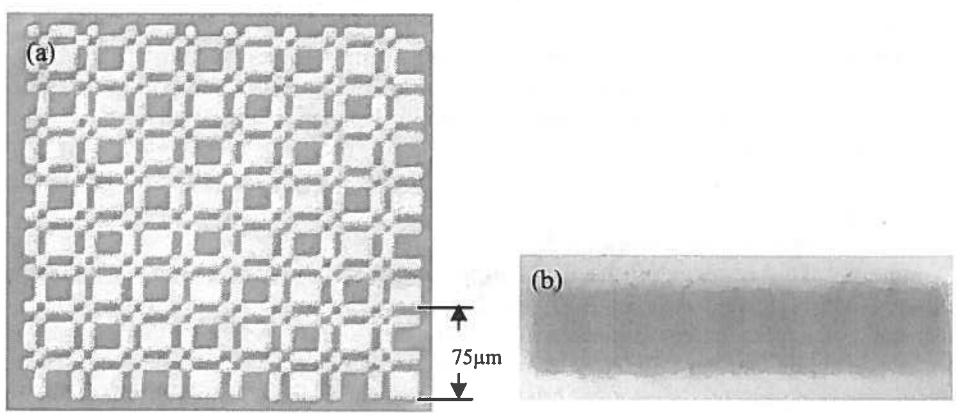

Fig. 4 Microscope photographs of the fabricated 6×6 Dammann grating with 4×4 period; (a) Top view, (b) Side view

We measured the diffraction efficiencies of Dammann gratings with far-field fan-out patterns of a He-Ne laser beam operating at 632.8 nm. Fig. 5 shows the far-field fan-out pattern generated from the grating with four layers. Although it has a brighter zero order spot at the center, the 6×6 pattern exhibited a uniform intensity distribution.

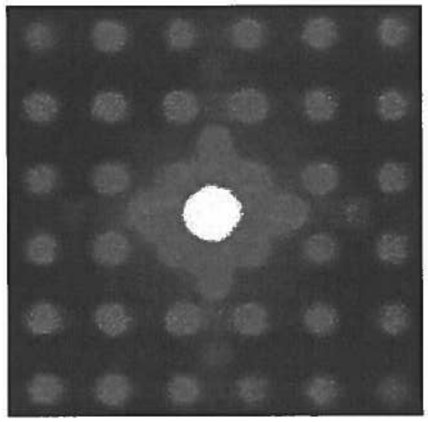

Fig. 5 Intensity distribution of far-field fan-out pattern

The relationship between the diffraction efficiency and the grating thickness for single layer and double layer is illustrated in Fig. 6(a). Although the single layer gratings have higher efficiencies, both types of gratings indicated similar dependency of the diffraction efficiency on the grating thickness as expected from Eq. (3). The diffraction efficiency increases with an increase in the thickness, reaches its maximum at around 80μm and decreases sharply afterward. When the maximum phase shift of the grating was considered to be π, the refractive index change was estimated to be ~3.9×10^{-3} from the Eq. (2). This estimated value was averaged along the optical axis because the upper part of the filament has higher refractive index change. During measurement of the diffraction efficiency, stronger scattering of the light and the higher orders of diffraction pattern was observed for the double layer gratings. The discontinuity of the refractive index profile at the interface between layers might be the source of additional optical loss, which resulted in lower efficiencies than those of the single layer gratings. In addition, gratings with different periods (p = 100 μm, 125 μm, 150 μm) were fabricated in order to examine its effect on the diffraction efficiency. Results indicated that the period of the grating had no influence on the diffraction efficiency. In the end, gratings were fabricated with higher scan speed of 4 mm/min to investigate the effect of homogeneity of a refractive index changed pattern on the diffraction efficiency. The numbers of layers were also increased up to 6 and the thickness of each layer was kept to ~30μm. From the results observed from Fig. 3, it was noted that the scan speed strongly influences the homogeneity of a refractive index change. Fig. 6(b) indicates that the diffraction efficiency was less than half the value from the Dammann grating fabricated with lower scan speed of 0.3 mm/min. This result confirms that the processing conditions resulting in homogenous refractive index change with high dimensional precision are optimal for the direct write fabrication of the Dammann gratings with a femtosecond laser. Although there is more room to increase the diffraction efficiency by increasing the number of periods, the stability of the laser power is an essential factor for long machining hours along with higher repetition rates for ultimate reduction in the machining time and cost effective fabrication.

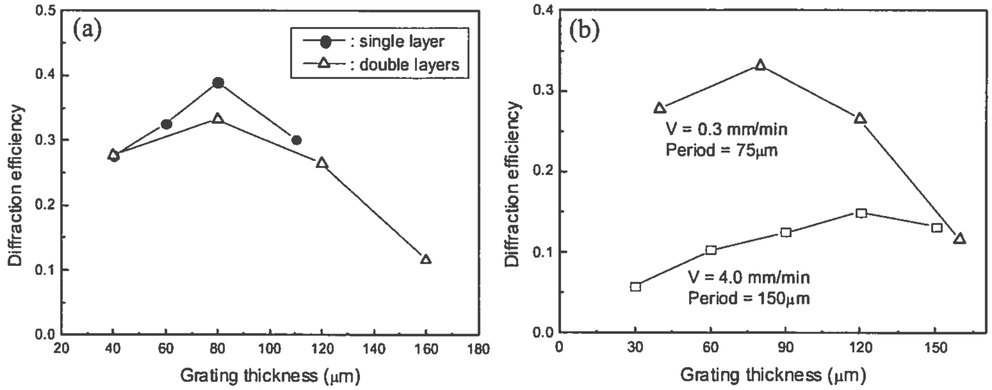

Fig. 6 (a) relationship between the diffraction efficiency and the grating thickness for single and double layers, (b) relationship between the diffraction efficiency and the scan speed

3. Conclusion

We have investigated the effects of processing parameters on the filamentation induced by refractive index change and established the optimal processing conditions to direct write of diffractive optical elements inside fused silica using a femtosecond Ti:Sapphire laser. 6×6 Dammann gratings with single and multiple layers were fabricated and their performance was evaluated. The diffraction efficiency had strong dependence on the grating thickness, the number of layers, and the scan speed. Single layer gratings provided higher efficiencies as compared to the multiple layers gratings. The grating period had no direct relationship with the resultant diffraction efficiency. A maximum diffraction efficiency of 38.8% was observed for a grating thickness of 80 μm fabricated in single layer.

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