Journal of the Korean Physical Society, Vol. 65, No. 10, November 2014, pp. 1559∼1565

Diffraction Efficiency Enhancement of Femtosecond Laser-engraved Diffraction Gratings Due to CO_2 Laser Polishing

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(Received 1 December 2013, in final form 2 July 2014)

This research demonstrates laser-assisted fabrication of high-efficiency diffraction gratings in fused-silica glass samples. Initially, femtosecond laser pulses are used to engrave diffraction gratings on the glass surfaces. Then, these micro-patterned glass samples undergo CO_2 laser polishing process. unpolished diffraction gratings encoded in the glass samples show an overall diffraction efficiency of 18.1%. diffraction gratings imprinted on the glass samples and then polished four times by using a CO_2 laser beam attain a diffraction efficiency of 32.7%. We also investigate the diffraction patterns of the diffraction gratings encoded on fused-silica glass surfaces. The proposed CO_2 laser polishing technique shows great potential in patterning high-efficiency diffraction gratings on the surfaces of various transparent materials.

PACS numbers: 42.55.-f, 42.55.Lt, 42.79.Dj, 42.40.Lx, 81.65.Ps
Keywords: CO_2 laser polishing, Femtosecond laser, Fused-silica glass, Diffraction grating, Diffraction pattern, Diffraction efficiency
DOI: 10.3938/jkps.65.1559

I. INTRODUCTION

Due to increasing demands for micro/nano-metric structures in diverse fields of science and technology, a large variety of machining technologies have come to the forefront of the research field: electron beam lithography [1], ion beam lithography [2], photo lithography [3], nano-imprint lithography [4], X-ray lithography [5], physical vapor deposition [6], chemical vapor deposition [7], and laser processing technology [8–26,30–33]. Since the discovery of the first functional laser, lasers have been considered as a promising tool for micro/nano-machining of various materials. The coherence and intense power of the laser beam make laser systems valuable to industry and researchers. During the last two decades, femtosecond lasers have attracted considerable interest due to their wide range of applications, especially for precise patterning of both transparent [9–13] and non-transparent materials [14–18]. For many years, the diffraction grating has been considered as a key component for the fabrication of various photonic and optical devices. Femtosecond-laser-assisted fabrication of diffraction gratings has shown great prospects in diverse fields [19–26]. Diffraction gratings have been fabricated using a femtosecond laser beam and various materials including ZnO crystal [19], metals [14,15,20], and glasses [9,21–26].

Using a femtosecond laser beam, researchers have patterned a diffraction grating on the surface of and inside soda-lime glass [9]. nano-scale diffraction grating has been encoded in fused silica glass by using femtosecond-laser-based holographic technology [21]. Another re-

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search group reported a femtosecond-laser-induced surface relief grating and an internal diffraction grating in glasses [22]. Periodic nano-metric diffraction gratings have also been reported to have been fabricated on silica glass by using two interfering femtosecond laser beams, *i.e.*, holographic technology [23]. A two-dimensional grating has been fabricated in fused silica and in foturan glass by means of femtosecond-laser-assisted processing technology [24]. Researchers have also proposed the fabrication of a polarization diffraction grating by using femtosecond-laser-assisted nano-structuring in fused silica glass [25]. Femtosecond-laser direct writing of a grating with a high quantum efficiency on erbium-doped Baccarat glass has also been reported [26]. Although a large number of research works have been conducted for fabricating diffraction gratings in glass materials, most of these diffraction gratings suffer from poor diffraction efficiency. These, efforts to enhance the diffraction efficiency have come to the forefront of the research field. Researchers have tried various technologies, including chemical etching, electron beams, and ion beams [2, 27–29], to improve the smoothness of the surface of the micro-patterned material, which would increase the diffraction efficiency of the diffraction grating. However, most of the technologies are somewhat complex, time consuming, and expensive, and require multiple-step processing. As a result, a simple processing technique is highly demanded.

In this paper, we proposed a novel technique to form a high-efficiency diffraction grating on the surface of a fused silica glass substrate. A key concept is to polish the diffraction grating on the glass surface to improve the diffraction efficiency. The proposed fabrication process for the diffraction grating involves in two-step processing: (1) femtosecond-laser-assisted fabrication of periodic micro-grooves on a glass surface and (2) CO_2-laser polishing of the micro-grooves encoded on the glass surface. In order to fabricate a periodic diffraction grating on a fused silica glass surface, we use a femtosecond laser beam to irradiate the sample's surface. The micro-grating engraved in the glass sample is polished several times by using a CO_2-laser-polishing technique. After four cycles of CO_2 laser polishing, the diffraction efficiency of the grating is increased from its initial value of 18.1 to 32.7%. In addition, we examine the diffraction pattern of the diffraction grating on a glass samples. Although CO_2 lasers have been extensively utilized for micro-patterning on a large variety of materials for several decades [30–33], application of a CO_2-laser-polishing system for smoothening the micro-patterns is a new concept. The proposed CO_2-laser-polishing technique is a promising tool for fabricating various photonic and optical devices, especially diffractive optical elements (DOEs) with an output of high efficiency.

II. EXPERIMENTS

1. Laser Systems

A Yb:KGW femtosecond laser system, that operates at a central wavelength (λ) of 1030 nm with a pulse repetition rate of 100 kHz and a pulse width of 250 fs, was utilized to fabricate the periodic grooves, *i.e.*, diffraction grating on a fused silica glass surface. During the experiments, we used fused silica glass samples with 900-μm thicknesses and a refractive index of 1.458 at a wavelength of 588 nm. The glass samples show high transparency with transmittances greater than 90% in the visible spectrum. The power and the energy of the linearly-polarized Gaussian laser beam was attenuated by using a rotatable quartz $\lambda/2$-wave plate connected to a polarizing beam splitter that transmitted the P-polarized laser beam while reflecting the S-polarized laser beam in the perpendicular direction (the S-polarized beam was blocked). We placed a beam expander (magnification $\approx 2\times$) in the optical path to expand the attenuated laser beam. The laser beam was focused using a 20× achromatic objective lens (numerical aperture (NA) = 0.4). The fused silica glass samples were mounted on a 3-axis linear translation stage. The translation stage had a resolution of 5 nm in the X, Y, and Z directions. The schematic diagram of the experimental setup is illustrated in Fig. 1(a).

A pulsed CO_2 laser beam, operating at a central wavelength of 10.6 μm with a pulse repetition rate of 5 kHz and a pulse width of 120 $\pm$ 40 μs, was used to polish the diffraction-grating-engraved glass surfaces. The femtosecond-laser-assisted micro-patterned glass samples were placed on a 3-axis translation stage with a resolution of 100 nm in all directions. We focused the CO_2 laser beam at the bottom surface of the micro-grooves by using a galvanometer scanner with a focal length of 170 mm. We used a confocal microscope with a resolution of about 120 nm to measure the surface roughness of the grating before and after the polishing. The surface roughnesses before and after three cycles of polishing were $\sim$ 4.2 μm and $\sim$ 0.78 μm, respectively. The CO_2-laser polishing system is depicted in Fig. 1(b).

2. Measurements and Analysis

In order to obtain the diffraction pattern and the diffraction efficiency of the diffraction-grating-encoded glass samples, we applied a He-Ne laser beam with a wavelength of 632.8 nm and a power of 890 W to the top of the diffraction-grating encoded glass samples. Using a power meter, we measured the input and the output powers of the He-Ne laser beam. For measuring the output power, we placed the power meter at the focal spots for different order diffracted beams. As a result,

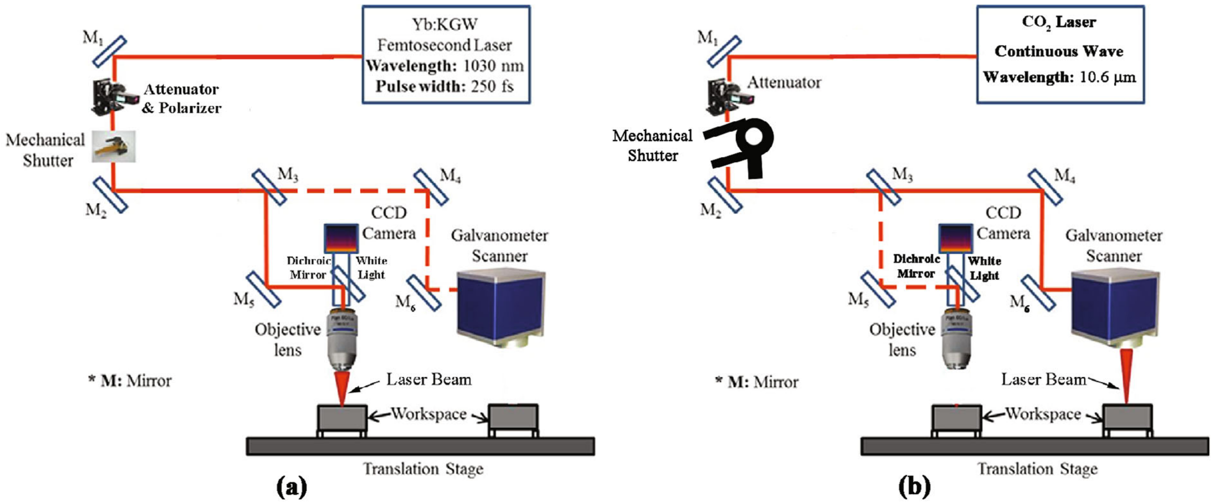

Fig. 1. (Color online) Schematic diagrams of the laser systems used to form a high-efficiency diffraction grating on a fused-silica glass surface: (a) femtosecond laser system and (b) CO$_2$ laser system.

we were able to calculate the diffraction efficiency of the diffraction-grating-imprinted glass substrates. To visualize the diffraction pattern of the grating, we placed a white screen on the opposite site of the laser beam by positioning the diffraction-grating-encoded glass samples in between. Under dark-room conditions, the diffraction patterns of the diffraction-grating-printed glass samples were visible on the screen, which images were captured using a high-resolution digital camera. The morphologies of the micro-structured glass surfaces were analyzed under a confocal microscope. We also captured the images of the diffraction grating by using an optical microscope. We also analyzed the profile images of the diffraction grating by means of an Alpha Step profiler.

III. RESULTS

To fabricate a high-efficiency diffraction grating on fused silica glass surface, our first step is to pattern a periodic micro-grating on the glass surface by using a femtosecond laser beam to irradiate the glass substrates. A femtosecond laser beam with a laser fluence of 6.32 J/cm^2 was applied to the glass surface through a 20× achromatic objective lens at a scanning speed of 1 mm/s in scanning steps of 40 μm. As a result, a periodic micro-grating with a linewidth of $\sim$20 μm and a grating period of 40 μm was printed throughout the sample area of 20 × 10 mm^2. We prepared six samples using the same specifications. Figure 2(a) illustrates an optical microscope image of the periodic diffraction grating fabricated on the surface of fused silica glass. The three-dimensional (3D) confocal microscope images of the unpolished diffraction grating are depicted in Fig. 2(b). The diffraction pattern of an unpolished diffraction grating engraved on a glass sample is shown in Fig. 2(c). An Alpha-step profile image of the grating is presented in Fig. 2(d). From the 3D image in Fig. 2(b) and the profile image in Fig. 2(d), evidently, that the fabricated diffraction grating has a flat-top shape, where the micro-grooves have inconsistent heights, widths, and shapes.

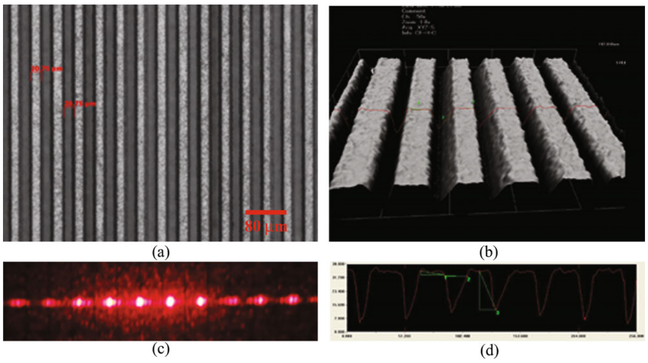

Fig. 2. (Color online) Femtosecond laser-induced diffraction grating (before CO$_2$ laser polishing) on a fused-silica glass surface fabricated at a laser fluence of 6.32 J/cm^2, a scanning speed of 1 mm/s, and a scanning step of 40 μm: (a) optical microscope image, (b) 3D confocal microscope image, (c) diffraction pattern, and (d) profile image, obtained from alpha-step measurements, of the diffraction grating.

After femtosecond laser patterning, the glass samples went through CO$_2$-laser polishing. The CO$_2$ laser beam with a laser power of 4.36 W was passed through a galvanometer scanner for repetitive polishing of the glass samples at a scanning speed of 100 mm/s. The spot size of the CO$_2$ laser beam was $\sim$20 μm. The number of laser polishings was varied in the range between one and six, Figure 3 shows optical microscope images, confocal microscope images, alpha-step profile images, and diffraction patterns of the diffraction gratings after CO$_2$-laser polishing. The CO$_2$-laser polishing improved the surface

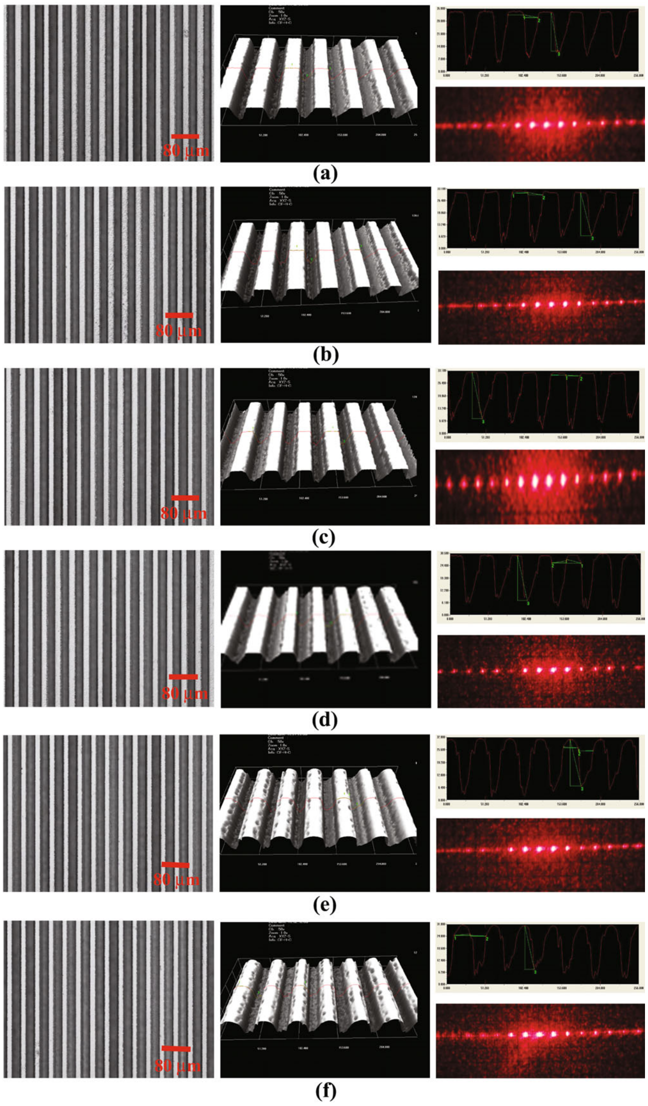

Fig. 3. (Color online) Optical microscope images, 3D confocal microscope images, profile images, and diffraction patterns of the diffraction grating on a fused-silica glass surface after CO_2 laser polishing: (a) one polishing, (b) two polishings, (c) three polishings, (d) four polishings, (e) five polishings, and (f) six polishings.

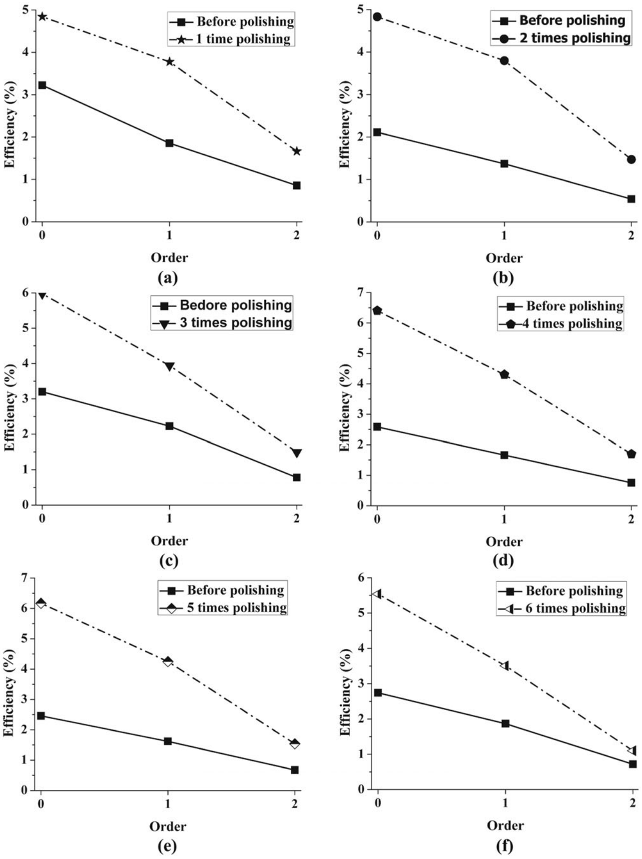

Fig. 4. Diffraction efficiencies for the 0^{th}-, 1^{st}-, and 2^{nd}-order diffracted beams for various numbers of CO_2 laser polishings: (a) one polishing, (b) two polishings, (c) three polishings, (d) four polishings, (e) five polishings, and (f) six polishings.

roughness of the diffraction grating; consequently, the surface of the micro-grating and the grooves had become smoother. The width of the grooves shows increases with increasing number of CO_2-laser polishings. For up to four laser polishings, the micro-grooves maintain a flat-top shape, which is evident from the 3D confocal microscope images and profile images of Figs. 3(a)−(d). However, beyond five CO_2 laser polishings, the top surfaces of the grating become curved, and bump-shape patterns develop on the glass surfaces, which is apparent from Figs. 3(e)−(f). The shape and the size (linewidth and depth) of the diffraction grating were altered during CO_2-laser polishing. Still, the diffraction patterns in all cases (including the unpolished glass sample) remained identical because of the constant period of the periodic grating.

In addition, we investigated the overall diffraction efficiency of the diffraction grating. The laser power of the He-Ne laser beam before the micro-grating engraved glass samples, known as the input power, was maintained at 890 μW. Before laser polishing, the overall power of the laser beam at the focal spot of the grating, also known as output power, was measured as 161.09 μW. The highest overall efficiency of 32.7% (output power: 291.03 μW) was achieved with four cycles of CO_2 laser polishing. We also examined the diffraction efficiency for different orders of the diffracted beams from the micro-grating-encoded fused silica glass samples of Figs. 2 and 3. Figure 4 depicts the diffraction efficiency for the 0^{th}-, 1^{st}-, and 2^{nd}-order diffracted beams for various number of CO_2-laser polishings.

The output power along with the overall diffraction efficiency and the diffraction efficiency for the 0^{th}, 1^{st}-, and 2^{nd}-order diffracted beams for different numbers of CO_2 laser polishings and for the unpolished glass samples are summarized in Table 1. In all cases, the high-

Table 1. Summary of the output powers and diffraction efficiencies for 0^{th}-, 1^{st}-, and 2^{nd}-order diffracted beams, and overall diffraction efficiencies for various numbers of CO_2 laser polished and unpolished glass samples.

Before Polishing: Input Power of 890 μW								
Sample	Overall Output Power (μW)	Output Power of Different Orders (μW)			Overall Efficiency (%)	Efficiency of Different Orders (%)		
		0^{th}	1^{st}	2^{nd}		0^{th}	1^{st}	2^{nd}
1	160	28.7	16.5	7.6	18.0	3.2	1.9	0.9
2	153	18.8	12.2	4.8	17.2	2.1	1.4	0.5
3	161	28.5	19.8	6.9	18.1	3.2	2.2	0.8
4	155	23.0	14.8	6.7	17.4	2.6	1.7	0.8
5	155	21.9	14.4	6.0	17.4	2.5	1.6	0.7
6	159	24.4	16.6	6.4	17.9	2.7	1.9	0.7
After Polishing: Input Power of 890 μW								
No. of Polishing	Overall Output Power (μW)	Output Power of Different Orders (μW)			Overall Efficiency (%)	Efficiency of Different Orders (%)		
		0^{th}	1^{st}	2^{nd}		0^{th}	1^{st}	2^{nd}
1st time	264	43.1	33.6	14.8	29.7	4.8	3.8	1.7
2nd time	264	43.0	33.8	13.1	29.7	4.8	3.8	1.5
3rd time	270	53.2	35.1	13.3	30.3	6.0	3.9	1.5
4th time	291	57	38.3	15.1	32.7	6.4	4.3	1.7
5th time	276	54.9	37.8	13.7	31.0	6.2	4.2	1.5
6th time	265	49.3	31.2	9.8	29.8	5.5	3.5	1.1

est diffraction efficiency was achieved after four cycles of laser polishing. Due to the profile change of the grating, the diffraction efficiency showed a decreasing trend from five cycles of laser polishing. For the 0^{th}-order diffracted beams, the highest diffraction efficiency of 6.4% was achieved after four cycles of laser polishing, where the highest efficiency for the unpolished micro-grating-engraved glass samples was 3.2%. For the 1^{st}-order diffracted beams, the highest diffraction efficiency of 4.3% was after four cycles of laser polishing, which is almost twice the diffraction efficiency of the unpolished glass samples (2.2%). For the 2^{nd}-order diffracted beams, a diffraction efficiency of 1.7% was achieved after one cycle and four cycles of laser polishing; whereas, the highest diffraction efficiency of the unpolished glass samples was 0.9%. The experimental results clearly indicate a considerable improvement in the diffraction efficiency of the polished diffraction grating compared to the unpolished femtosecond-laser-induced diffraction grating.

IV. DISCUSSION

A diffraction grating consist of a set of slits and grooves with spacing d (grating's period), where d must be wider than the laser's wavelength in order to cause diffraction. When a plane wave of wavelength λ_i is irradiated perpendicularly on the grating, the incident light interacts with the periodic grating. The diffracted light is composed of the summation of the interfering wave components coming out from each slit of the periodic grating. The path length to each slit of the grating varies at any plane through which diffracted light may pass. When the path difference of light between adjacent slits is equal to the wavelength of the incident light λ_i (in this case, λ_i = 632.8 nm), the phases will add together and reach a maximum. When the incident light impinges upon the grating at normal incidence, the diffracted light gains maxima at angles θ_m, where m is an integer representing the order of the diffracted light. We can relate the grating period and the angles θ_m by using the following equation, also known as the grating equation [34]:

$$d \sin\theta_m = m\lambda_i \ . \tag{1}$$

When the incident light is incident upon the grating at any arbitrary angle θ_i, the grating equation becomes as follows [34]:

$$d(\sin\theta_i + \sin\theta_m) = m\lambda_i \ . \tag{2}$$

By rearranging Eq. (2), we obtain the diffracted angles for the maxima for various orders of diffracted light:.

$$\theta_m = \arcsin\left(\frac{m\lambda_i}{d} - \sin\theta_i\right) \ . \tag{3}$$

During our experiments regarding the diffraction pattern and the diffraction efficiency, the incident laser beam was applied perpendicularly on top of the diffraction grating structured in the glass sample. As a consequence, we can consider $\theta_i = 0$ in Eq. (3). As a result, the 0^{th}-order beam remains undiffracted. On the other hand, m can be either positive or negative, resulting in diffracted orders on both sides of the 0^{th}-order beam. For a single-layer diffraction grating with a 40-μm period, the 1^{st}-order diffracted beams are diffracted at an angle of 0.91°. whereas the 2^{nd}-order beams are diffracted at an angle of 1.81°.

From our experimental results, we find that a variation in the number of laser polishings changes the size, shape, and depth of the grating. Consequently, curved gratings are evident after five laser polishings (shown in Figs. 3(e) and (f)). Until four CO_2-laser polishings, the diffraction efficiency increased significantly. However, the diffraction efficiency showed a decreasing trend with increasing number of laser polishings beyond four. The curved shape of the grating beyond four laser polishings might have influenced the diffraction efficiency. In addition, we examined the diffraction pattern for the diffraction grating and found similar patterns for all micro-grating-imprinted glass samples. Because the period of the grating remained constant for all the glass samples, naturally the diffraction patterns for all cases be alike. We can consider the proposed CO_2-laser-polishing process as a promising tool for the fabrication of various photonic/optical devices based on diffractive characteristics.

V. CONCLUSION

In summary, we proposed a novel technique of CO_2 laser polishing for enhancing the diffraction efficiency of a diffraction grating on a fused-silica glass surface. The anticipated processing technique was comprised of a double-step process consisting of femtosecond-laser direct writing of a diffraction grating on a glass surface followed by CO_2 laser polishing. A significant improvement in the diffraction efficiency was achieved due to CO_2 laser polishing. The highest diffraction efficiency was achieved after four cycles of laser polishing for all the cases. Due to a change in the flat-top shape of the diffraction grating beyond four cycles of CO_2 laser polishing, the diffraction efficiency started decreasing again. We also examined the diffraction patterns of the glass samples with diffraction gratings and observed similar diffraction patterns for the polished and the unpolished samples. We strongly believe that the proposed CO_2 laser polishing technology will have a wide range of applications in diverse fields of science and technology.

ACKNOWLEDGMENTS

This research was supported by the 2013 research fund of Chosun University, Korea. This work was also supported by the “Research on ultra-precision laser machining and optical information technology” Project through Gwangju Institute of Science and Tchnology in 2013.

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