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Selective ultrashort laser fabrication of thick and thin volume-phase gratings

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Abstract

Volume-phase gratings (VPGs) are fabricated in CdSxSe1-x quantum dot doped borosilicate glass at different repetition rates. As the heat accumulation effects caused by the repetition rate lead to changes in the diameter of the modified volume (from 1 to 10 µm), the selective fabrication of thick or thin gratings can be benefitted when the different repetition rates are exploited. Microscope images of the cross-sections of the laser modified zone at different inscription distances from the surface, repetion rates and pulse energies are presented. From this images, widths and thicknesses have been measured. Diffraction properties of VPGs fabricated at different pulse energies have been studied. We present results on the far-field diffraction efficiencies and the near-field light intensity distribution (Talbot effect).

Keywords: Laser material processing, Ultrashort laser, Integrated Optics Devices, Volume-Phase Gratings, Near-field diffraction, Talbot effect.

1. Introduction

Volume-phase gratings are optical devices that diffract light, which is a fundamental operation in spectroscopy [1] or laser systems [2]. By definition, a VPG is a transparent material that has a spatially periodical modulation of the refractive index. In comparison with amplitude-gratings, where the transmission of light is periodically modulated, the VPGs offer the advantage that almost non incident light is loss in the propagation through the device, and therefore, diffraction efficiencies of almost 100% can be achieved.

Few studies have been reported on the near-field diffraction properties of the femtosecond laser fabricated VPGs [3]. Among the different peculiarities that are observed in the microscale propagation of the

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light, one of the most studied phenomenon is the Talbot effect or also called self-imaging. Caused by the interference of waves with quadratic relative phases, when a grating is illuminated with a collimated monochromatic light, exact images of the illuminated grating are formed at some specific distances from the device. As this effect results from the wave-like behavior of the laser physics, it is not surprising that it can be found in other do-mains of physics such as electron microscopy, plasmonics or quantum mechanics. Moreover, it has led to a variety of applications in optical lithography, micro-patterning, metrology or interferometry [4].

In this work, a complete analysis of both near-field and far-field diffraction of femtosecond laser fabricated VPG is presented. An VPG with a far-field first order efficiency of up to a 20% and a near-field contrast of 0.5 have been fabricated. In order to accomplish this, the effect of the heat accumulation regime in the fabrication process was exploited in order to maximize the width of the laser modified material zone. In comparison to the multiple scanning technique, which is based on producing a wider laser material zone by overlapping multiple laser-passes, this new approach offers a single-pass process that leads to a significant reduction of the fabrication time cost.

2. Methods

2.1. Experimental

The laser process of fabrication was made with a 500 kHz diode-pumped ultrafast fiber amplifier Satsuma system of λ=1030 nm (Fig. 1). VPGs were fabricated in the bulk of a borosilicate glass doped with a 1 % of embedded CdSxSe1-x semiconductor nanocrystals of 3.9 nm radii (OG530 Schott Glass Inc.). Laser processing of this material have been reported to show a high refractive index change [5]. Under conditions of tight focusing (a laser spot-size of 2.5 µm, NA=0.4), material modification leads to permanent change of the optical properties (refractive index, absorption, photoluminescence…) of the processed zone [6]. In order to generate the 3D structures, a computer controlled motorized stage was utilized.

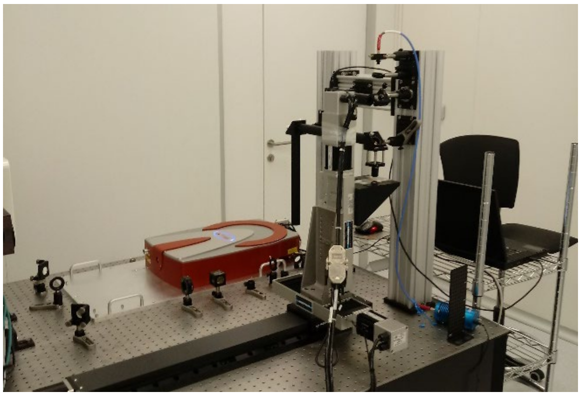

Fig. 1. Image of the 500 kHz diode-pumped ultrafast fiber amplifier Satsuma system.

The femtosecond laser fabricated VPGs were posteriorly characterized with microscopy inspection and diffraction analysis. In order to study the far-field and near-field diffraction regimes, a 4 mW HeNe cw laser of λ=633 nm was used. Far-field diffraction generated light intensities patterns were acquired with a spectrometer Oriel® MS257™, while the near-field diffraction was measured with a microscope imaging setup.

2.2. Equations

Talbot effect is the near-field phenomenon of light intensity patterns self-imaging through the light propagation direction. These replication planes happen at certain distances $Z_T = p^2/\lambda$. As the diffraction pattern generated by the VPG comes as a periodical distribution of light intensity peaks and digs, we define the contrast of the image as:

$$C = (I_{max} - I_{min})/(I_{max} + I_{min} \qquad (1)$$

Where the C=1 means that the intensity of the light in the dark lines in the image are zero, and C=0 means no distinction between the lines, that is to say, the light distribution is homogenous ($I_{max}=I_{min}$).

3. Results

3.1. Inscription distance from the glass surface

When an intense laser pulse propagates inside a material, different effects can happen. Even when self-focusing effect is negligible, effects due to the spherical aberrations of the objective lens can affect the exact location where the structures are inscribed. In order to have control over the bulk zone where structures are fabricated, we have calibrated the positions of our motorized stage with the real distances from the glass surface where the structures are inscribed (Fig. 2).

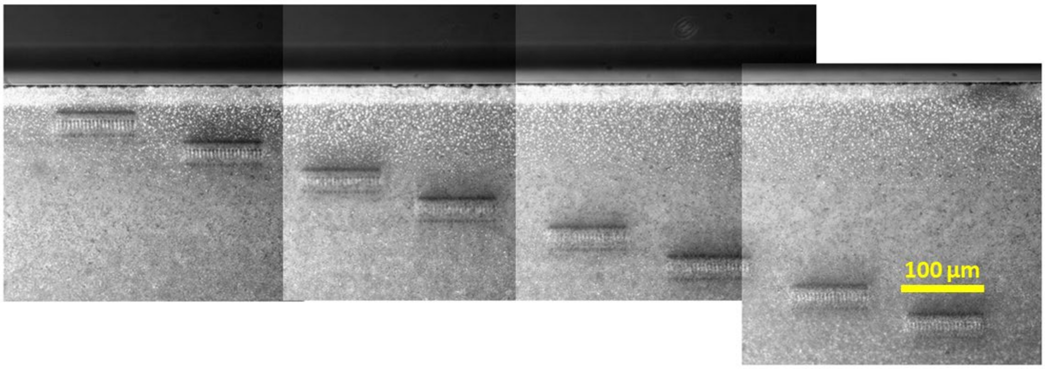

Fig. 2. Control of the distance of the inscribed structures from the glass surface

3.2. Repetition Rate cross-sections

Depending on the pulse repetition rate of the structure fabrication process, the thermal behavior of the material-laser interaction is different. As long as thermal energy dissipation time exceeds the time between pulses (commonly stated at repetition rates >200 kHz), the average temperature of the modified zone increases with successive pulses, which leads to modification zones bigger than the laser spot-size [7].

Microscope images that confirm this phenomenon are presented in Fig.3. Fabrication processes were made at 1 µJ and scanning velocity of 2 mm/s. The experiment of 1 kHz, 250 kHz and 500 kHz were made at a distance from the surface of 400 µm and the experiment of 100 kHz at 200 µm. As it is observed, two qualitatively different modification zones are presented. The measured width of the modified zone for 1 kHz and 100 kHz are a=1.4 µm and a=1.2 µm respectively, while for 250 kHz and 500 kHz, they are a=8 µm and a=7.4 µm. Note that as these results are wider than the laser spot-size of 2.5 µm, the modification mechanism at 250 kHz and 500 kHz should not be mediated by irradiation.

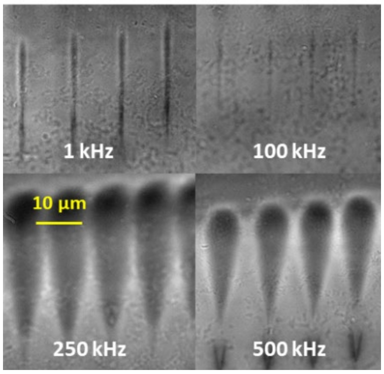

Fig. 3. Microscope image of the cross-sections of laser modified zones at different repetition rates.

As diffraction properties of VPGs depend strongly on the duty cycle of the structures, this results can provide a selective way of optimizing VPGs with different periods. This could be exploited as using low repetition rates for small periods of ~3 µm, and high repetition rates for periods of >10 µm.

3.3. Energy pulses cross-sections and far-field efficiency

In order fabricate VPGs of 10 µm, an optimization of the pulse energy have been made. The study was made at 500 kHz because results from the Fig. 3 suggest that is the processing condition that gives the fittest duty cycle for periods of 10 µm.

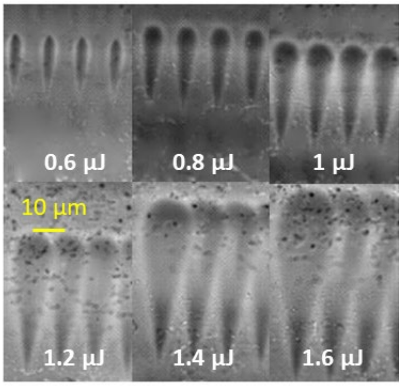

Fig. 4. Microscope image of the cross-sections of laser modified zones at different pulse energies.

Fig. 4 show how energy pulses affect the width and the thickness of laser modified zones. For laser pulses exceeding 1 µJ, the width of the modified zones fulfills the size of the period, which have consequences in the diffraction properties of the VPGs. The measured far-field diffraction efficiencies increases and then decreases as pulse energy augmented. A maximum first order efficiency 20% is achieved for the fabrication process at 1 µJ pulse energy.

3.4. Near-field efficiency for different energy pulses

Since the material modification is arranged in a periodic way, Talbot effect happens for VPGs fabricated with femtosecond laser. This effect can be sharpened or flattened if the fabrication process is optimized in a way that the phase difference generated by the micro-structures is enhanced. The measurement of the light intensity distribution in one of the Talbot planes provides the maximum contrast configuration, that is to say, the sharpest self-image locations along the light propagation direction z.

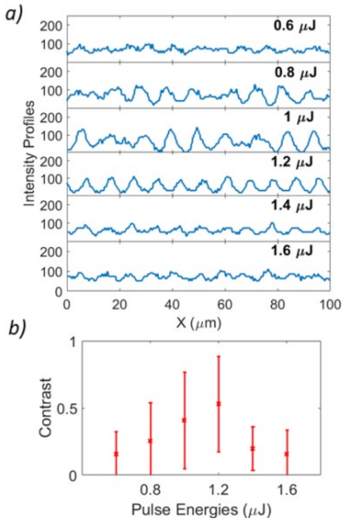

Fig. 5. Near-field diffraction efficiencies for VPGs fabricated at different pulse energies. a) Intensity profiles in x. b) Contrasts for different pulse energies.

Fig.5 a) shows the different intensity profiles generated by the VPGs fabricated at different pulse energies for a fixed location in z at one of the Talbot planes. As it is observed in the image, a similar behavior to the diffraction efficiencies in the far-field is observed; as pulse energy increased, a central maximum contrast is achieved and then it starts to diminish (Fig. 5 b)). Although the maximum value does not coincide for both cases (in the far-field is 1 µJ and in the near-field is 1.2 µJ), the reason behind the tendency looks to be the same; these values coincide with a duty cycles of ~0.5, the optimum condition for VPG diffraction, while for bigger pulse energies, the width of the laser modified zone starts to exceed the period size, and diffraction diminishes.

4. Conclusions

We have observed the effect of the heat accumulation when different repetition rates are applied in the fabrication process. This phenomenon has been exploited in order to fabricate high-efficiency VPGs that can selectively adequate to different period sizes. Control over the depth of the inscribed structures, along with the micro-scope images of the cross-sections and the measurement of diffraction properties (near- and far-field) have been necessary in order to characterize the final device. Based on this results, we conclude that the selective use of different repetition rate regimes during the fabrication can result in an advantageous method for selectively fabricating thick- or thin-gratings.

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