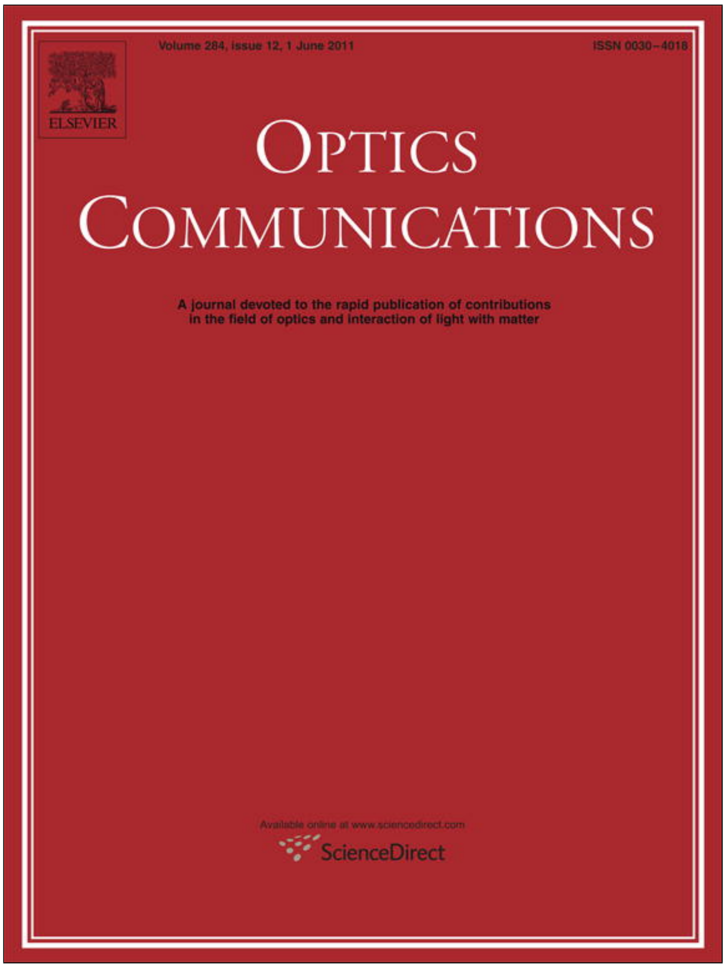
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Optical characterization of PMMA phase gratings written by a 387 nm femtosecond laser

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ABSTRACT

We report on the fabrication of optical Bragg type phase gratings in polymethyl methacrylate substrates by a femptosecond Ti: Sapphire laser. As for their optical characterization, a spatially resolved microscopy interferometric technique is used to investigate the two-dimensional distribution of the refractive index change produced by the irradiation process. The technique gives a direct and quantitative two-dimensional profile of the index of refraction in irradiated PMMA, providing information on how the fabrication process depends on the laser irradiation.

1. Introduction

Recently, there has been much interest in applying focused femto-second laser pulses at high repetition rate to induce various localized microstructures near the focal point of laser beam in transparent materials. Focused femto-second laser pulses induce structural changes inside the transparent materials, such as glass and polymers, due to nonlinear absorption at high peak powers. The induced refractive index change can be used to fabricate the three-dimensional microstructures and optical devices [1]. Several photonic structures have been realized in glass crystals [2–8]. Structures induced by the irradiation with near infrared femto-second laser pulses have been investigated in various polymer materials with different glass transition temperatures [9].

Waveguide fabrication within polymethylmethacrylate (PMMA) by femto-second laser pulse irradiation has been reported [10,11]. Diffractive optical elements using various polymeric materials have also been fabricated by translating the laser focus area [12–14]. These experiments have shown that the refractive index in the laser focus area increases as compared with that before the irradiation.

Different mechanisms have been proposed for explaining these, as changes in polymer density, or structural changes induced by photodecomposition processes or also by tensile stress. Direct observation of femto-second light-induced refractive index changes is thus necessary for understanding and controlling, namely, scanning speed, laser energy and laser pulse duration [15]. These parameters can be changed independently but their effects are unavoidably superposed upon each other. Phase contrast microscopy has been used for optical analysis of phase grating structures [16]. In this work we report on quantitative spatially resolved interferometric measurement of Bragg type phase gratings inside PMMA produced by femto-second laser irradiation. Spatially resolved interferometric measurement of refractive index offers the great advantage of being a direct measurement and allows to obtain a two-dimensional phase map of the index changes across the surface of the irradiated sample [17].

2. PMMA grating writing procedures

The writing system is schematically shown in Fig. 1. Poly (methyl methacrylate) (PMMA) samples with a thickness of ~5 mm, and an area of 2 cm × 2 cm were used in the experiments.

The samples were irradiated by a regeneratively amplified Ti: Sapphire laser pulsed at a 1-kHz repetition rate, with pulse duration of 250 fs at a central wavelength of about 800 nm. The output was linearly polarized horizontally and the pulse energy was 0.105 μJ in the TEM mode with a beam diameter of ~3 mm. The laser beam was attenuated by a diffractive optic attenuator and frequency doubled by a BBO crystal, generating second harmonic signal (SHG) at 387 nm. This wavelength causes increased refractive index changes compared to the fundamental wavelength, due to enhanced nonlinear absorption. A neutral density (ND) filter was placed between the reflection mirrors to keep the integrated laser fluence below the damage threshold. The beam passed through two UV mirrors to reduce the residual IR radiation. Optical refractive modifications were produced by repeated irradiation with a number of overscans. The beam was focused to ~8 μm diameters by a 20× Nikon microscope objective with a 0.45 numerical aperture, 10 mm

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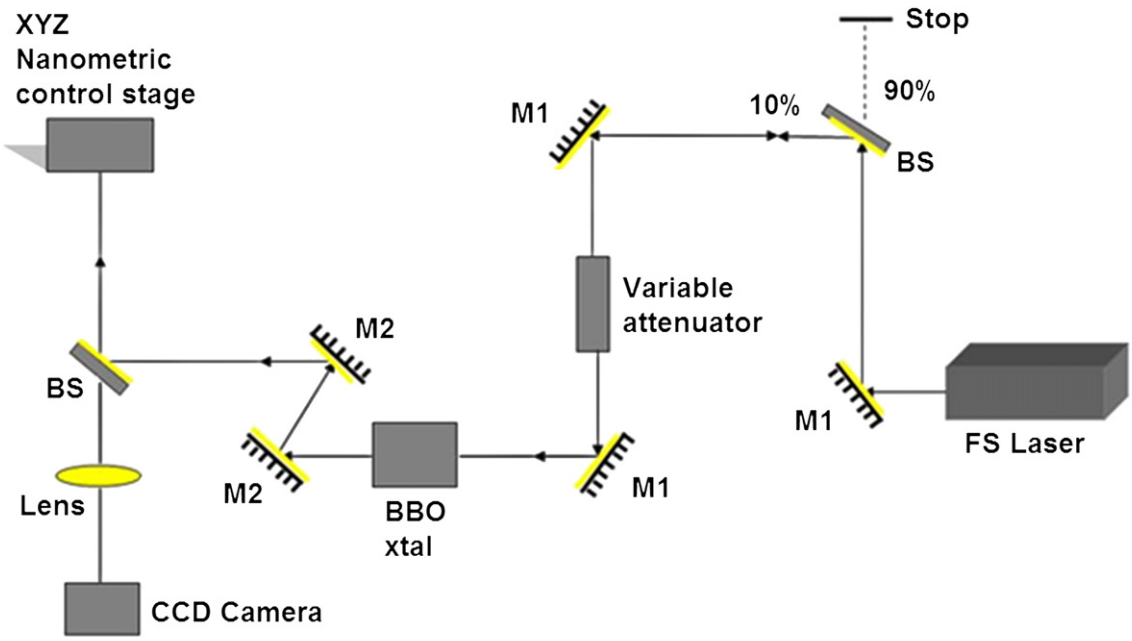

Fig. 1. The experimental setup of sub surface irradiation technique, M_1 50 mm diameter IR mirrors, and M_2 50 mm diameter UV mirrors.

focal length and a working distance of 8 mm. The focal point was located 200 μm beneath the sample surface. The sample was mounted on a PC controlled Aerotech x-y-z translation stage (ANT-25LV) of 2.5 nm resolution. The scanning speed of the writing process was 1.25 mm/s and a CCD camera was used to record the fabrication process. The writing process was performed by translating the PMMA sample along the horizontal *x*-direction so that the laser beam scribed sequentially parallel structures, line by line. The translation speed was kept constant during the irradiation processes. The thickness of the internal written phase grating was approximately $d = 700$ μm. Fig. 2 shows microscopic images of two diffraction grating structures written by scanning the PMMA sample under the fs laser at a speed of 1.25 mm/s under different irradiation conditions. The phase grating of Fig. 2(a) was written with a pulse energy of 0.102 μJ and 5 overscans, and that of Fig. 2(b) with 0.105 μJ and 32 overscans.

3. Refractive index analysis

A preliminary test of the written phase grating was done with a probe He–Ne laser beam passing through the grating. The Bragg diffracted order yields an estimate of the grating period of about $p = 40$ μm. To assess the diffraction type, we determine the Q parameter [18] given by $Q = 2\pi\lambda d/np^2$, where $\lambda = 633$ nm is the probe wavelength and $n = 1.491$ is the PMMA refractive index. In our case we have $Q = 1.17$, a value greater than 1, indicating a Bragg-type grating. The refractive index modification was inferred from the measurement of the first-order diffraction efficiency η_1 defined by dividing the first-order diffraction beam intensity by the intensity of the total transmitted probe light. The diffraction efficiency calculated by measuring the beam intensity in the first order diffraction spot with a CCD camera was $\eta_1 = 0.573$.

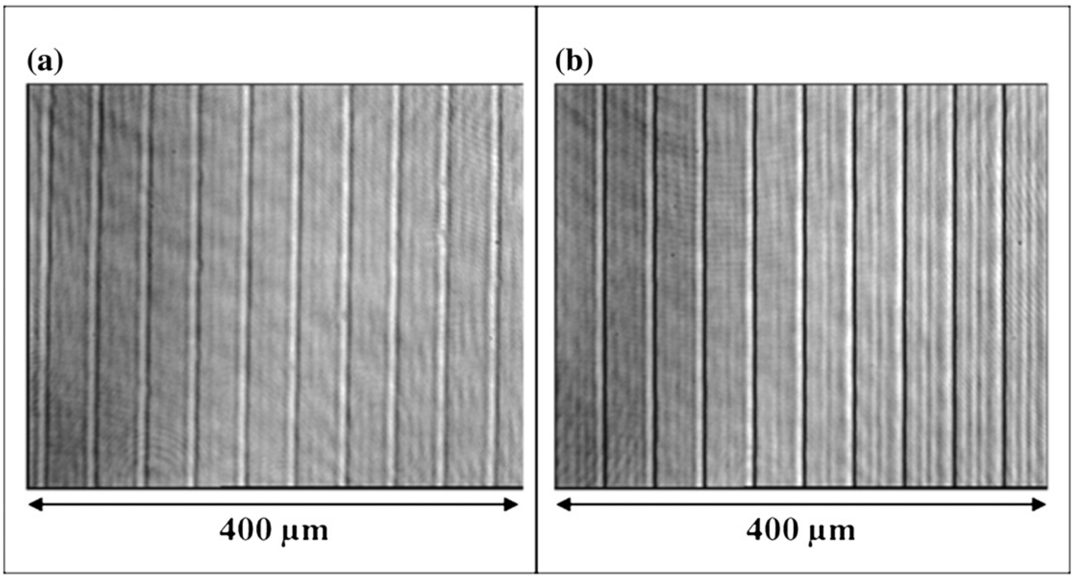

Fig. 2. Top views of the UV written phase gratings in PMM with a scan speed of 1.25 mm/s: (a) pulse energy of 0.102 μJ and 5 overscans, and (b) pulse energy of 0.105 μJ and 32 overscans.

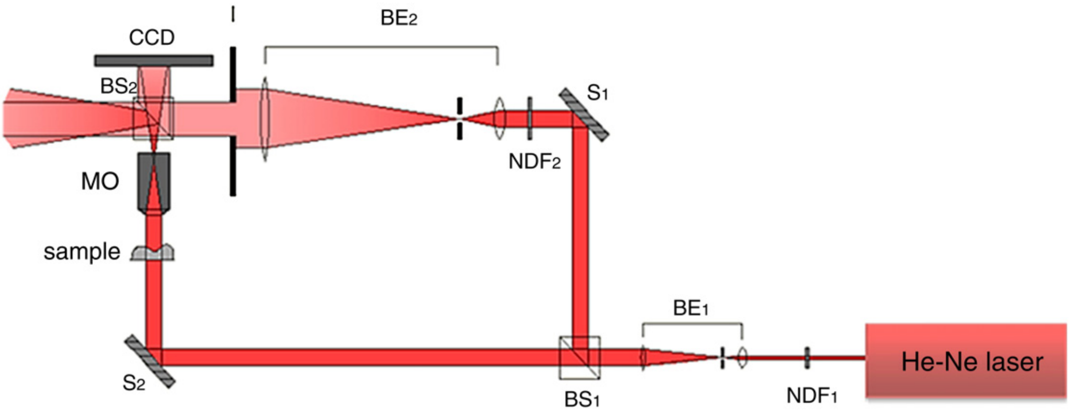

Fig. 3. Mach–Zehnder interferometric system in microscopic configuration. BS_1 and BS_2 are beam splitters. NDF_1 and NDF_2 are neutral density filters; BE_1 a spatial filter and beam expander for the incident laser light; BE_2 a spatial filter and beam expander to generate a plane wave front reference beam, and MO a microscope objective 10×.

In order to investigate refractive index changes induced by the fs laser irradiation region of the sample, we performed a two-dimensional visualization and spatially resolved optical analysis of the induced refractive index profile by using a digital holographic technique. The advantage of this technique is the possibility of numerically reconstructing both the amplitude and phase of the complex wavefield transmitted by the sample under investigation [19-21]. We employed the Mach–Zehnder interferometric setup shown in Fig. 3. A He–Ne laser provided the probe laser radiation and the written phase gratings were inserted in the object arm of the interferometer. Neutral density filters NDF_1 and NDF_2 were employed to control the laser intensity and to adjust fringe visibility. A 10× microscope objective (MO) of numerical aperture N.A = 0.3 was placed after the sample to allow the desired magnification of the grating structure. A collimated and expanded reference wave interferes at small angle with the object wave transmitted by the

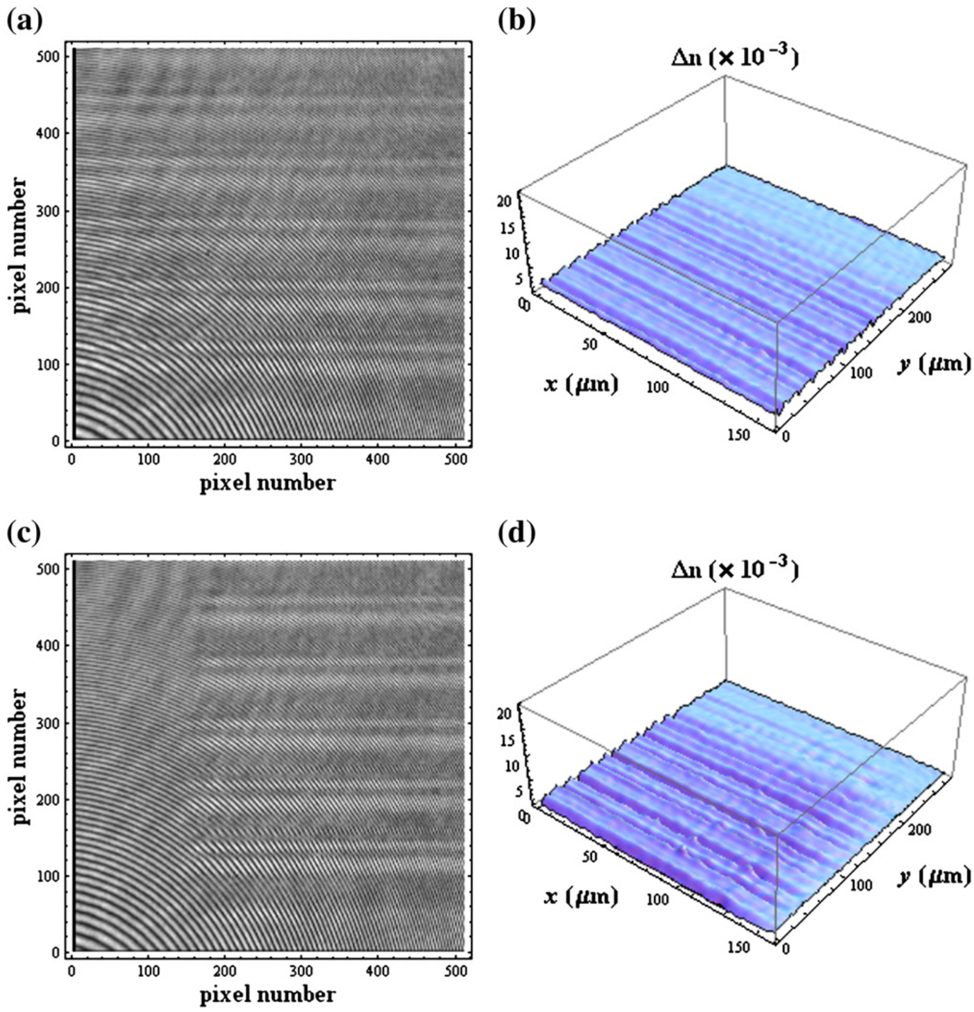

Fig. 4. 3D visualization of the spatial distribution of the index of refraction calculated from the interference patterns: (a) and (c) digitized interferograms of UV written phase gratings in PMMA with a scan speed of 1.25 mm/s and (b) and (d) corresponding refractive index maps.

phase grating at the surface of a CCD camera (752×582 pixels and square pixel of size 8.16 μm), followed by frame grabber and PC.

Fig. 4(a) and (c) show two interferometric patterns of PMMA laser irradiated samples, digitized in a square matrix 512×512 pixel. Ring fringes whose centers are located in the lower part of the frame in figure are caused by the interference between the wavefront from the microscope objective and the reference wave. The patterns show clearly the interference fringe modifications in correspondence of irradiated zones across the PMMA sample surface. We performed a double-exposure digital holographic interferometry by recording two holograms without and with the grating inserted in the object arm of the interferometer.

The phase change distribution $\Delta\phi(x,y)$ across the x–y plane of the sample is related to the optical path difference between the object field and reference field due to the presence of the sample into the interferometric setup. The technique accounts for the wave propagation diffractive effects from the object plane to the recording plane of the CCD array, since it allows reconstructing the wave field directly at the object plane. The lateral resolution, i.e., the size of the reconstruction pixel depends on the reconstruction distance, on the wavelength and on the number of pixel used in the reconstruction algorithm. We used a calibrated target at the sample position to measure and to evaluate the actual magnification of the microscopic system. The reconstruction distance for numerically retrieving the phase distribution across the sample surface is in our case 120 mm and the size of the reconstruction pixel is 18.2 μm, which scaled for the measured actual magnification M ~9 gives a final value of 2 μm. The ultimate spatial resolution is determined by the diffraction limit, which is proportional to the wavelength and inversely proportional to the angular distribution of the light observed [22].

It is possible to derive the refractive index changes $\Delta n(x,y)$ from the phase change profile by the relationship $\Delta n(x,y) = \lambda\Delta\phi(x,y)/2\pi d$ where $\lambda = 633$ nm is the wavelength and d is the thickness of the sample. The three dimensional distributions of the refractive index of the phase gratings are shown in Fig. 4(b) and (d). The maps are numerically retrieved from the corresponding digitized interferograms shown in Fig. 4(a) and (c).The periodicity of the structure is quite evident from the reconstructed 3D maps and it is related to the periodicity of the laser writing process. These results show that femtosecond laser pulses induce localized optical phase variations along the laser scanning direction resulting in positive refractive index changes with average peak values Δn_{max} of the order of 1.4×10^{-3} and 2×10^{-3} respectively, for the sample written with 0.102 μJ, 5 overscans and for that written with 0.105 μJ, 32 overscans. This is consistent with the expectation that if the material is repeatedly exposed, the refractive index changes increase owing to the accumulated laser fluence. The measured induced phase variations $\Delta\phi$ are always less than 2π in our case but, phase unwrapping algorithms can be also be used for measuring large phase changes induced by laser radiation. The refractive index changes are in agreement with measurements in waveguides written in PMMA samples by using photochemical techniques [14].

4. Conclusions

In conclusion Bragg type phase gratings are produced in bulk polymethyl methacrylate by UV femto-second laser irradiation. Gratings are due to refractive index changes inside the polymeric material. We have reported a spatially resolved interferometric technique and demonstrated that it can be used as an efficient method for non-invasive measurement of the induced refractive index changes. The spatial resolution of the technique is limited by the probe beam wavelength, the microscope objective numerical aperture and the pixel size of the recording detector array. The results suggest that efficient modification of the material can be accomplished for a regime of repeated pulses with long pulses, 250 fs with low laser fluence.

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References

[1] A. Baum, P.J. Scully, M. Basanta, C.P. Thomas, P.R. Fielden, N.J. Goddard, Opt. Lett. 32 (2007) 190.
[2] K.M. Davis, K. Miura, N. Sugimoto, K. Hirao, Opt. Lett. 21 (1996) 1729.
[3] K. Miura, J. Qiu, H. Inouye, T. Mitsuyu, K. Hirao, Appl. Phys. Lett. 71 (1997) 3329.
[4] D. Homoelle, S. Wielandy, A.L. Gaeta, N.F. Borrelli, C. Smith, Opt. Lett. 24 (1999) 1311.
[5] J. Qiu, P.G. Kazansky, J. Si, K. Miura, T. Mitsuyu, K. Hirao, A.L. Gaeta, Appl. Phys. Lett. 77 (2000) 1940.
[6] H. Sun, Y. Xu, S. Juodkazis, K. Sun, M. Watanabe, S. Matsuo, H. Misawa, J. Nishii, Opt. Lett. 26 (2001) 325.
[7] J. Qiu, C. Zhu, T. Nakaya, J. Si, F. Ogura, K. Kojima, K. Hirao, Appl. Phys. Lett. 79 (2001) 3567.
[8] L. Luo, D. Wang, C. Li, H. Jiang, H. Yang, Q. Gong, J. Opt. A. 4 (2002) 105.
[9] S. Katayama, M. Horiike, M. Urairi, K. Hirao, N. Tsutsumi, Opt. Rev. 10 (4) (2003) 196.
[10] K. Ohta, M. Kamata, M. Obara, Proc. SPIE 5430 (2004) 172.
[11] S. Sowa, W. Watanabe, T. Tamaki, J. Nishii, K. Itoh, Opt. Express 14 (2006) 291.
[12] P.J. Scully, D. Jones, D.A. Jaroszynski, J. Opt. A Pure Appl. Opt. 5 (2003) S92.
[13] S. Katayama, M. Horike, K. Hirao, N. Tsutsumi, Jpn. J. Appl. Phys. 41 (2002) 2155.
[14] A. Baum, P.J. Scully, M. Basanta, C.L.P. Thomas, P.R. Fielden, N.J. Goddard, W. Perrie, P.R. Chalker, Opt. Lett. 32 (2007) 190.
[15] A. Baum, P.J. Scully, W. Perrie, D. Jones, R. Issac, D.A. Jaroszynski, Opt. Lett. 33 (2008) 651.
[16] D. Kip, Appl. Phys. B 67 (1998) 131.
[17] T. Kreiss, Handbook of Holograpfic Interferometry — Optical and Digital Method, Wiley-WCH, 2005.
[18] A. Yariv, Optical waves in crystals (2002, Wiley, John & Sons).
[19] G. Zito, A. Finizio, S. De Nicola, Optics Express 17 (2009) 18843.
[20] L. Zhu, C. Zhou, T. Wu, W. Jia, Z. Fan, Y. Ma, G. Niu, Appl., Opt. 49 (2010) 2510.
[21] E. Shaffer, N. Pavillon, J. Kühn, C. Depeursinge, Opt. Lett. 34 (2009) 2450.
[22] A.J. den Dekker, A. van den Bos, J. Opt. Soc. Am. A 14 (1997) 547.