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Laser Interferometry for Study of Nonlocal Response of Optically-Transparent Ion-Implanted Polymers*

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Abstract. We demonstrated that the laser interferometry can be applied to inspect the nonlocal response of optically-transparent ion-implanted polymers, in particular polymethylmethacrylate (PMMA). Ion-modified material in 100 nm-thick layer on the surface of a plane-parallel PMMA plate implanted with silicon ions (Si^+) at an energy of 50 keV and fluence of 3.2×10^{15} Si^+/cm^2, was studied. The thermal nonlinearity of the material in the ultrathin ion-modified layer was induced by cw laser irradiation at a relatively low intensity in a localized region. The in-plane laser-induced thermooptic effect in the near(sub)surface layer of Si^+-implanted PMMA was probed by interferometric imaging.

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1 Introduction

Ion implantation is well established technology for modification of optical properties of the surface of polymers and the produced materials have found advanced applications [1,2]. In particular, subsurface planar structures fabricated by ion implantation of poly-(methyl methacrylate) (PMMA) have been reported for use in miniature components for integrated lightwave systems [3,4], in compact optical devices [5,6] and other photonic applications based on the highly controllable modification of the optical refraction index of the ion-implanted material in the near-surface region of this highly transparent thermoplastic. Of great importance for such applications of ion-implanted polymers are their thermo-optical properties.

The goal of the present study is to use Interferometric imaging to estimate the nonlocal response of PMMA subjected to a low-energy (50 keV) silicon ion

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(Si^+) implantation at a fluence of 3.2×10^{15} Si^+/cm^2. Being very sensitive, the optical interferometric techniques are able to probe the surfaces and subsurfaces. In our case, an interferometric two-beam (pump-probe) technique was applied to derive the in-plane nonlocal response of Si^+-implanted PMMA by employing continuous wave (cw) laser sources: a pump ($\lambda = 532$ nm) and probe ($\lambda = 633$ nm).

2 Experimental

Si^+-implanted PMMA under study was a plane-parallel plate of size 1×1 cm^2 and thickness of 5 mm from optical-quality PMMA implanted with silicon ions at an energy of 50 keV and fluence of 3.2×10^{15} cm^{-2} [7]. The laser interferometry set-up is schematically shown in Figure 1. The interference patterns were obtained after reflection from the ion-modified surface of the Si^+-implanted PMMA sample that was located on the one of the two arms of the interferometer, instead of a mirror. The desired phase shift is introduced by the reference beam with one-axis linear positioning stage (NanoX 200, Piezosystem Jena) by applying DC voltage provided by piezo-control unit. In the pump-probe technique applied, we used a diode-pumped solid-state cw laser ($\lambda = 532$ nm, 3.5 mW) as a 'pump' laser, whose beam was directed at an incidence angle of 30° on the sample to induce a refractive index modulation based on the absorption of the pump. He-Ne laser (wavelength $\lambda = 632.8$ nm, 0.3 mW laser power on the sample) was employed as a 'probe' laser source illuminating the interferometer. The interference pattern was acquired by a CCD video camera (Sony XC-38).

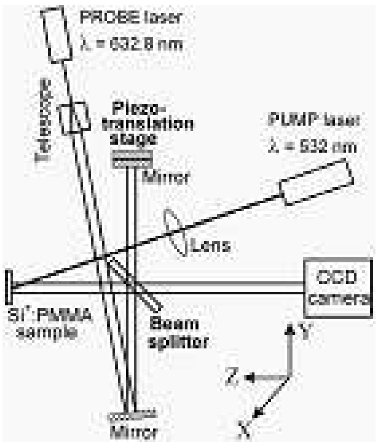

Figure 1: Scheme of the experiment setup.

3 Results and Discussion

As reveals our optical spectroscopy investigation, ion-modified layer is located in a ~ 100 nm-thick region within the PMMA substrate, beneath the surface [8]. The optical characteristics of the material in this ultrathin subsurface planar layer significantly differ from those of PMMA [7-10]. In contrast to the optically-transparent PMMA, the light absorption of Si^+-implanted PMMA was 35% at the wavelength $\lambda = 532$ nm.

In our experiment, pump-laser-induced optical phase shift was provoked by thermo-optical effect caused from the absorbed pump light power at the illuminated location of a finite size, subsequently dissipated as a heat energy. In consequence, a laser-induced change of the refractive index (Δn) of Si^+-implanted PMMA occurs. As known, the heat conduction in thermal media with thermal nonlinearity [11] results in a spatially nonlocal change of the optical refractive index [12]. Thus, for the ultrathin ion-implanted layers formed within optically-transparent polymers upon cw laser irradiation one can consider a nonlocal thermooptic effect of laser-induced nonlinear change Δn. The latter can be assessed by optical interferometry through the corresponding optical phase change ($\Delta\Phi$). Actually, by interference measurements the distribution $\Delta n(x, y)$ in the main plane of the ion-implanted layer (the X-Y plane, Figure 1) can be obtained from the spatial distribution of the optical phase shift $\Delta\Phi(x, y)$ induced by the pump. From intensity distribution of the interference pattern in the *X*-*Y* plane as recorded by the CCD camera, one can determine the optical phase shift between the reference and object beams that interfere [13].

Figure 2 (a,b) presents the interference phase distribution (the phase profile $\Phi(x, y)$, i.e. the spatial distribution of the relative optical phase shift in the object arm of the interferometer) calculated from recorded interferograms by means of phase-stepping method [13-15]. The phase profile obtained with pump was referenced to the one with no pump. Thus, the pump-induced optical phase change $\Delta\Phi(x, y)$ (Figure 2c) reflects the pump laser-induced refractive index change $\Delta n(x, y)$. The latter is related to the nonlocal response [16] of examined ultrathin layer of Si^+-implanted PMMA.

As seen from Figure 2(c), even at the relatively low intensity of the pump laser used in our experiment $\Delta\Phi$ is considerable and reaches 2π, and the $\Delta\Phi$ distribution is much broader than the pump beam spot itself. The size of this extended region is indicative for the range of nonlocality. In fact, the laser-induced thermo-optic effect extents over almost the whole sample surface. The large thermal nonlinearity of Si^+-implanted PMMA assessed in the main plane of the ion-modified layer is reasonable in view of the formation of carbonaceous material in this ultrathin planar subsurface layer where a strong in-plane spreading of the heat flux due to thermal diffusion-like processes takes place.

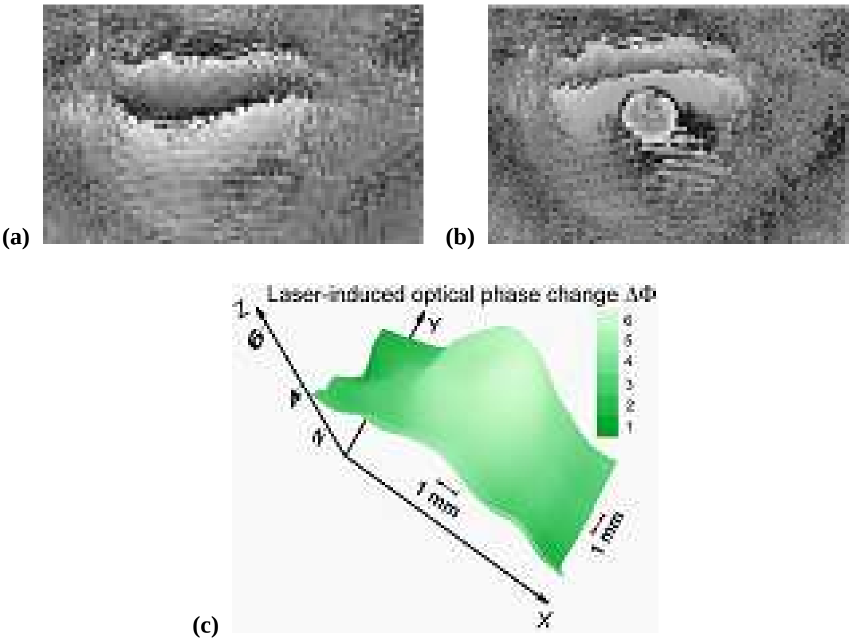

Figure 2: Optical phase profiles: (a) no pump; (b) pump present; (c) pump-induced optical phase change $\Delta\Phi$ calculated from data in (a, b).

4 Conclusions

We report the first application of the reflection interferometry to analyze the nonlocal response of ion-implanted polymers. The thermooptic effect observed in reflection is exploited to characterize the nonlocal response of Si^+-implanted PMMA by use of interferometric two-beam (pump-probe) technique and corresponding analyses. The interference phase distribution in the plane of the ion-implanted layer is indicative for the thermal nonlinearity of the material in this layer.

By numerical analysis, the in-plane nonlocal response of Si^+-implanted PMMA was derived from interferometric images captured by a digital camera. Due to the significant absorption of light, the carbonaceous material in the ultra-thin ion-implanted layer formed within the optically-transparent PMMA polymer exhibits a sizable laser-induced change of the refractive index, as well as a large laser-induced optical phase change. A strongly expressed nonlocality in the millimeter scale was found for this thermal medium, that has to be taken into account when consider photonic applications of ion-implanted optically-transparent polymers (devices operating in transmittive, diffractive and/or reflective mode).

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