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Photoinduced record of waveguide structures in films of polymethylmethacrylate doped with beta-diketonatoboron difluorides

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ABSTRACT

In this paper the possibility of using the novel polymeric photosensitive medium for the fabrication of integrated optics elements was demonstrated. The medium is based on PMMA doped by 2,2-difluoro-4-(9-anthracyl)-6-methyl-1,3,2-dioksaborine. Planar and strip waveguides with the attenuation losses less than 2 dB/cm were fabricated in the layer of the medium. The photoinduced recording of the diffraction grating with the spatial frequency up to 2500 mm^{-1} and diffraction efficiency ~5% in such waveguides was demonstrated. The possibility to improve the diffraction efficiency of recorded gratings up to 47% by chemical treatment was demonstrated.

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1. Introduction

Integrated photonics is a promising technological basis for modern high-speed optical communication systems, and optical processing devices. Using this basis it is possible to design new microfluidic biochips, high-sensitivity sensors, radiation sources and detectors, low-and high-frequency switches and modulators of light energy [1]. Polymers are among the most promising materials for the fabrication of different photonic devices. Polymers in comparison with crystalline and glass materials are better suited for mass-fabrication of photonic devices with the use of photolithography, nanoimprint and soft-lithography [2]. Another important advantage of polymers consists in ability to vary their optical properties by doping of different chemical additives. This allows one to obtain photosensitive, photopolymerizable, electro-optical and laser polymer materials with a refractive index (RI) ranging from 1.3 to 1.8, which significantly exceeds the RI range of silicon compounds [3]. Photosensitive polymer materials are of interest for the design of active and passive elements of integrated optics since these materials allow one to use the methods of direct optical recording both flat and three-dimensional photonic components through low-threshold nonlinear processes in polymers [4].

Polymethylmethacrylate (PMMA) doped with β-diketonate complexes of anthracene-containing boron difluoride ($AntBF_2$) is a relatively new and poorly studied material. It was found that bulk PMMA+$AntBF_2$ samples exhibit sufficiently good photosensitivity and demonstrate a possibility of the optical holograms recording with a spatial frequency up to 2500 mm^{-1} and diffraction efficiency higher than 65% [5]. However, the optical properties of thin waveguide layers of such material and fabrication methods of integrated optics elements based on PMMA+$AntBF_2$ films are not currently studied in details. Thus such a study is the aim of the present work.

2. Planar waveguides fabrication

The PMMA+$AntBF_2$ waveguide films are fabricated using a spin coating [6]. First, granules of PMMA with the $AntBF_2$ additive and 1% of amyl acetate, which is used as a plasticizer, are dissolved in the dichloroethane. The resulting chemical solution is spin-coated on fused silica substrate. Then, after the film solidification we carried out the annealing at 90 °C for 1 h to remove the mechanical stress in the films and evaporate the solvent residues.

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This temperature is higher than the PMMA's softening temperature, however, such a condition does not lead to the thermal destruction of the $AntBF_2$ photoactive additive [7]. To ensure the uniformity of the films obtained we used dichloroethane as a solvent [8]. We chose the dichloroethane since it has significantly lower evaporation rate in comparison with the chloroform, which was used for the fabrication of bulk PMMA+$AntBF_2$ samples in [5]. However, it should be noted that dichloroethane dissolves the photoactive additive slower than the chloroform. As a result, optical properties of obtained PMMA+$AntBF_2$ films may differ from that of the bulk samples in [5].

The RI of the films fabricated is measured by the interference method [9]. The results presented in Fig. 1a shows that the RI of the PMMA+$AntBF_2$ film is less by ~0.001 than the RI of the bulk sample with the same concentration of the $AntBF_2$ additive. However, for both bulk samples and films the RI value exceeds the refractive index of pure PMMA (see curve 1 in Fig. 1(a)), which allows one to use the latter as a waveguide substrate. However, in the present paper we used ready-made optically polished fused silica substrate. It significantly facilitates the fabrication process of the experimental samples.

Fig. 1(a) also shows spectral dependencies of the absorption coefficient $\alpha(\lambda)$ measured in transmission. The analysis of the data presented indicates that the optical recording can be carried out in the wavelength range 400–410 nm as well as for the case of the bulk samples [5], while the readout of the recorded structure can be performed in spectral window (640–1100 nm) which is useful for polymer photonics [3].

We have also found that in the waveguide mode the light attenuation of the films is much higher than in transmission. The fact can be explained as follows. A light scattering on a surface roughness and refractive index inhomogeneity of the film makes a significant contribution to the light attenuation in addition to the film absorption coefficient. It should be noted that the presence of such inhomogeneity is heavily determined by the rotation frequency (ν) of the spin coater. Moreover, ν determines the average thickness of the planar waveguide and, therefore, the composition of its waveguide modes (the single-mode regime at $\lambda=655$ nm is realized at the film thickness ranging from 0.5 to 1.5 μm [10]). Fig. 1(b) shows the experimentally measured [11] dependence of the waveguide attenuation coefficient α_w (curves 1 and 2) and the average film thickness d (curve 3) on the rotation frequency ν. As it seen the attenuation coefficient α_w is minimal at $\nu \sim 3000$ rpm ($\alpha_w=1.6$ and 4.2 dB/cm at 1%- and 3%-$AntBF_2$ concentrations, respectively). Apparently, such rotation frequency provides the best conditions of the PMMA+$AntBF_2$ spreading on the fused silica substrate and the minimal coater vibrations. It is also seen that the rotation frequency provides the film thickness ~1.2 μm and, correspondingly, the single-mode propagation regime. In accordance with the results obtained we believe that the additional decrease of the coater vibration is unnecessary. To investigate the optical properties of waveguides recorded in PMMA+$AntBF_2$ films we used experimental setups depicted in Fig. 2(a).

3. Experimental results

Interference field of two coherent light beams B_1 and B_2 (Fig. 2a) with a wavelength $\lambda=405.9$ nm and intensity ~10 W/cm^2 is used to record refractive index diffraction gratings in waveguide films. After the recording process the fabricated gratings are illuminated by the readout beam B_3 with the wavelength $\lambda=655$ nm in transmission. In this regime the diffraction efficiency of the refractive index gratings is quite low owing to the low film thickness. However, the data about the intensity of the first diffraction maximum in accordance with [12] can be used to calculate the amplitude of the light-induced refractive index change (δn) of recorded refractive index gratings. Fig. 3 (curve 1) shows the dependence of δn on the spatial frequency Ω of refractive index gratings obtained for waveguide film with the 1% concentration of the $AntBF_2$ additive. This curve coincides well with the same dependence obtained for bulk sample [5]: for both cases the maximum amplitude of the refractive index change is $\sim 1.1\times10^{-4}$. However, it turns out that the phase depth for received gratings can be increased by creating a surface profile [13]. This can be achieved by etching the waveguide films in a solution of isopropanol and acetone in a proportion of 1:4. The results of correspondent measurements show that the depth of the surface relief of the recorded gratings increases monotonically with etching time Δt. However, at $\Delta t > 1.5$ min the waveguide film is peeled off from the substrate surface owing to the excessive PMMA softening under the influence of the solvent. Therefore, to increase the depth of the surface relief, the etching process is divided into several cycles. Each cycle includes the etching process

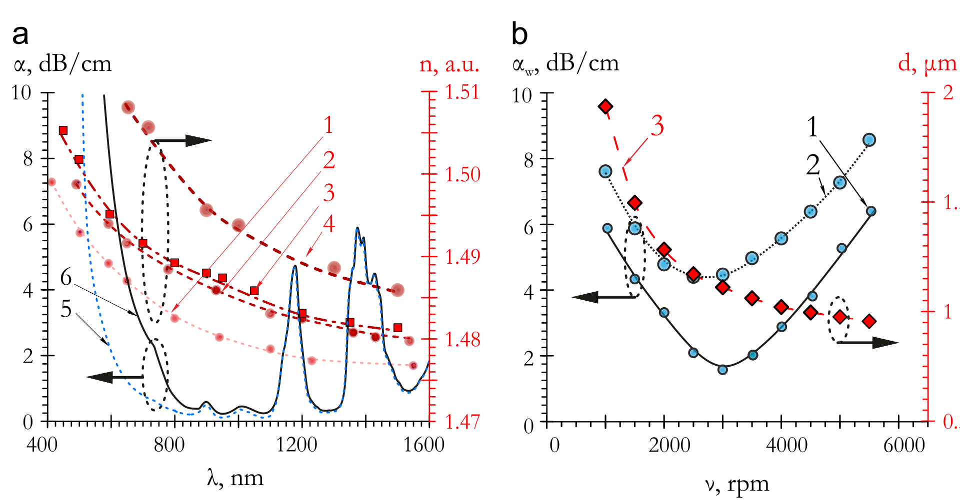

Fig. 1. Optical properties of PMMA films doped with the $AntBF_2$ additive: (a) Dispersion curves of the pure PMMA film (curve 1), PMMA+1%$AntBF_2$ film (curve 2), bulk sample of PMMA+1%$AntBF_2$ (curve 3), PMMA+3%$AntBF_2$ film (curve 4) and absorption spectra of PMMA+1%$AntBF_2$ (curve 5) PMMA+3%$AntBF_2$ (curve 6) films. (b) Attenuation coefficient α_w (at $\lambda=655$ nm) of PMMA+1%$AntBF_2$ (curve 1) and PMMA+3%$AntBF_2$ films (curve 2) and their thickness d (curve 3) versus the rotation frequency ν of the spin coater (The waveguide losses are measured by the prism-sliding method [11]).

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