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Electro-optically tunable diffraction grating with photoaligned liquid crystals

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ABSTRACT

This work shows the possibility of fabricating one- and two-dimensional diffraction structures based on liquid crystals photoaligned with the layers of photosensitive azobenzene poly(ester imide). The gratings involve a micron-sized planar-twisted nematic alignment. The diffraction efficiency of these gratings is controlled by a uniform electric field applied across the cell. The electro-optical measurements showed short switching times (0.8 ms and 7 ms for τ_{rise} and τ_{decay} respectively) and low driving electric fields ($1.5\ \mathrm{V}/\mu\mathrm{m}$) of 1st order diffracted light. The LC grating is regarded as an amplitude grating in the low electric field region and a phase grating in the high electric field region. Moreover the diffraction efficiency is polarization-independent in the wide range of external electric fields.

1. Introduction

Switchable diffraction gratings have numerous applications in various photonic devices that can perform beam steering, beam shaping and other modifications of light intensity or phase [1–7]. Liquid crystals (LCs) have become natural candidates for application in such devices because of their ability to change the orientation of the molecular director upon application of an electric field, what leads to a change in an effective refractive index of the medium experienced by a propagating light beam. Especially nematic liquid crystals (NLCs) is an ideal choice as uniaxial materials for such uses due to great optical parameters such as e.g. large optical birefringence, low viscosity [8].

There are several ways for fabricating the devices that induce the diffraction of the electromagnetic wave over the LC structure. One uses liquid crystal composites [9,10], photocrosslinkable polymer liquid crystals [11,12], microrubbing process [13,14] whereas the other are based on an array of parallel electrodes, allow many configurations [15–17]. However, with conventional nematic LCs, most of such gratings show slow response time, high driving voltage and they often are complicated to produce. An alternative method, which is attractive because of its simplicity utilizes the photoalignment of the LC medium by photosensitive materials [18,19]. Photoalignment is a very useful technique for fabricating LC diffractive optical elements as the periodic orientation of LC molecules can be easily obtained optically via exposure through a photomask [20] or holographic recording [21]. Various photocrosslinkable polymers were developed for use in the photoalignment of LCs [22–24] Azobenzene-containing polymers (azopolymers) are among the potential photoaligning materials that may generate excellent LC alignment at low irradiation dose [19]. As a consequence of many *trans–cis–trans* photoisomerization cycles initiated by the absorption of linearly polarized light of a proper wavelength, the rod-like azobenzene moieties tend to orient perpendicularly to the beam polarization direction [25]. Due to reversible photochemistry azopolymers offer rewritability during re-exposure with light of different polarization state, what changes the molecular alignment. However, the generated azochromophore orientation may not be sufficiently stable due to the disordering processes including the azochromophore and the main chain motions [26]. Although the light-generated molecular orientation in these azopolymers is a very efficient process, the temporal stability of the induced order after ceasing the excitation beam may not be satisfactory high when the practical uses are considered. However, by a proper design of the polymer chain and chromophore chemical architectures the materials meeting the criterion of low relaxation rate of the azochromophore orientation in the dark may be developed.

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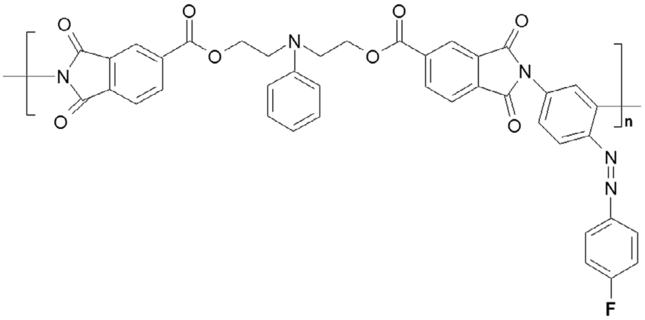

Fig. 1. The chemical structure of the poly(esterimide).

Herein, we report on a relatively simple fabrication of one- and two-dimensional diffraction gratings based on a patterned NLC photoalignment involving periodically alternating planar-twisted nematic domains. The planar-twisted nematic patterned alignment has been demonstrated recently by Wang et al. using the SD1 azo-dye photoactive substrate layer and a unidirectionally rubbed polyimide film for the second cell substrate [27]. However the rubbing process has many problems, such as unevenness, lack of controllability, all related to its mechanical contact operating principle. Therefore, in this work, the patterned alignment is generated with the use of the custom synthesized azopoly(esterimide) serving as the photoaligning layer for both of the LC cell substrates. The polyimide used in our work has a photosensitive azobenzene group in the side chain and is characterized by low degree of relaxation of the azochromophore orientation in the dark. Therefore, the generated TN and HG arrangement persist unchanged for a one year for the time being. Moreover polyimide used in this work exhibits excellent adhesion to the ITO-glass substrate. Therefore, the adhesion promoters are unnecessary. This greatly simplifies the technology of obtaining liquid-crystal diffraction gratings. Diffraction efficiency and electro-optic measurements show attractive performance of the devices mainly due to excellent electro-optical properties and polarization-independence in the wide range of external electric fields. It has been shown that these diffraction gratings can be amplitude or phase dependent on applied external electric field. This kind of LC polarization-independent gratings can be used in spatial light modulators and projection-type display systems.

2. Experimental

2.1. Materials

The synthesis, physicochemical and photoresponsive properties of amorphous azobenzene functionalized poly(esterimide) (denoted as PESI-F) (Fig. 1) have been described recently [28]. The absorption maxima due to electronic transitions of *trans* azochromophores of PESI-F are located at 350 and 450 nm. The polymer glass transition temperature is of 145 °C. The capability of the PESI-F material for aligning the nematic liquid crystals has been shown to us very lately [29].

The nematic liquid crystalline material 1892 [8] with positive dielectric anisotropy ($\Delta\varepsilon > 0$) has been prepared at the Institute of Chemistry, MUT, Warsaw, Poland. In order to remove the degeneracy in the sign of the twist of the director, a small amount of right-handed optically active dopant ((S)-4-isothiocyanatobiphenyl-4-yl 2-methylbutyl ether) has been added to the nematic liquid crystal mixture. This induces a uniform, right-handed twist of the molecular structure within twisted nematic (TN) regions of diffractive structures. The optical parameters of the NLC mixture used in the experiment are shown in Table 1.

Table 1
The optical parameters of the NLC mixture.

	1892 mixture
N-Iso [°C]	79.9
Δn [20°C, 589 nm]	0.19
$\Delta\varepsilon$ [20°C, 1.5 kHz]	7.39
η [mPa s]	10.54
Chiral dopant [wt.%]	0.5

2.2. The diffraction liquid crystal cell preparation

The N,N dimethylformamide (DMF) solution of PESI-F (1 wt%) was spin-coated (3500 rpm) onto the clean glass substrates coated with ITO conductive transparent layers. Then, the solvent was evaporated at 180 °C for 1.5 h. The thickness of the obtained PESI-F films was in the range of 15–20 nm (evaluated with the ellipsometric method). The PESI-F films were irradiated using the 200 W, Xe–Hg fiber optic UV lamp (Hamamatsu LC8) as a light source (λ = 360 nm). Linearly polarized UV (LPUV) radiation was obtained using a Glan–Taylor prism polarizer. The intensity of LPUV radiation was 15 mW/cm^2. A schematic drawing of the subsequent steps applied for fabrication of one-dimensional LC diffractive structure is showed in Fig. 2.

After the azopolymer deposition, both of the cell substrates were uniformly irradiated by LPUV light of a horizontal polarization direction. Next, one of the cell substrates was additionally irradiated by an orthogonally polarized UV beam passing through the amplitude photomask (chrome pattern on a quartz substrate) with periods Λ = 15 μm. This step allowed for inducing the chromophore reorientation in the non-masked areas perpendicularly to the electric field vector (and hence to the molecular orientation in the obscured regions). The irradiation time in each step was 1 h. Two-dimensional diffractive structures were created in a similar way but the amplitude mask with the two-dimensional pattern was used (of 75 μm period) in this case. The LC cells assembled from two substrates with an 1 cm^2 active area were prepared in the clean room. The cell thickness was stabilized by the 5 μm thick glass spacers. All cells were filled with the NLC mixture using capillary action. Provided the LC molecule orientation is maintained across the cell the alignment pattern forms two types of domains, that is a planar (homogeneous-HG) and twisted nematic. Due to a spatially periodic variation of the refractive index, the whole system comprises a diffraction grating.

3. Results and discussion

3.1. Polarized optical microscopy

In order to verify the LC molecular orientation the liquid crystal cells were placed under a polarizing microscope between crossed polarizers. Fig. 3 presents the observed images together with a schematic representation of the LC director orientation in the adjacent areas of 1D and 2D gratings. The dashed and solid arrows represent the director alignment on the top and the bottom substrates, respectively. The alignment is either planar (in the areas with parallel arrows) or twisted nematic (in the areas with orthogonal arrows). Different alignment directions of the adjacent domains cause the variations in the LC refractive index. The black regions visible under crossed polarizers correspond to a planar LC alignment in a direction parallel to the polarizer optical axis. The regions possessing the TN configuration correspond to the bright fields in Fig. 3(C) and (D). This is because the Mauguin condition is fulfilled for the fabricated cells [30], ensuring rotation of polarization direction by 90° exactly. Well resolved periodic areas indicate a good liquid crystal alignment.