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Electrically tunable two-dimensional holographic polymer-dispersed liquid crystal grating with variable period

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ABSTRACT

An electrically tunable two-dimensional (2D) holographic polymer-dispersed liquid crystal (H-PDLC) grating with variable period was fabricated by inserting a cylindrical lens in a conventional holographic interference beam. The interference between the plane wave and cylindrical wave resulting in varying intersection angles on the sample, combined with dual exposure along directions perpendicular to each other, generates a 2D H-PDLC grating with varied period. We have identified periods varying from 3.109 to 5.158 µm across a 16 mm width, with supporting theoretical equations for the period. The period exhibits a symmetrical square lattice in a diagonal direction, with an asymmetrical rectangular lattice in off-diagonal locations. With the first exposure at 2 s and the second exposure at 60 s, the phase separation between the prepolymer and liquid crystal was most evident. The diffraction properties and optic-electric characteristics were also studied. The diffraction efficiency of first-order light was observed to be 13.5% without external voltage, and the transmission efficiency of non-diffracted light was 78% with an applied voltage of 100 V. The proposed method provides the capability of generating period variation to the conventional holographic interference path, with potential application in diffractive optics such as tunable multi-wavelength organic lasing from a dye-doped 2D H-PDLC grating.

1. Introduction

Liquid crystal (LC) based diffraction grating has come to the forefront of technology in recent years [1–3]. This grating has high birefringence and high sensitivity to an externally applied electric field, which leads to potential applications in optics, optoelectronics and photonics. Two-dimensional (2D) gratings represent an efficient way to distribute an optical signal into an array of receivers, attracting the attention of many research groups [4–15]. Several techniques have been proposed for fabricating switchable 2D LC diffraction gratings, such as a pixel-wall photomask used to control the rate of polymerization during UV exposure [4], two-step exposure employing the orthogonal overlaying of two 1D gratings [5], one single-step exposure using the interference from four beams [6], a single diffraction element used to create a three-beam interference pattern [7], and polarization holography using crossed assembling of 1D polarization holograms recorded at the photo aligning substrates [8]. Furthermore, several types of LC materials have been used: cholesteric LC and dye-doped cholesteric LC [9–12], blue-phase LC [13,14], and ferroelectric LC [15].

Among all types of LC materials, interest is primarily focused on holographic polymer-dispersed liquid crystal (H-PDLC), which is widely used in fabricating switchable lens [16], optical switches [17], holographic 1D gratings [18], and 2D diffraction gratings [4–7,19]. The resulting structure of H-PDLC based 2D gratings is composed of layers of hardened polymer separated by layers of LC droplet-rich planes. The diffraction efficiency of the grating could be switched by using an appropriate external driving voltage. 2D H-PDLC gratings have been reportedly applied in lasing emission [20], optically switchable filters and spectroscope [21] and can be fabricated using direct laser writing, such as four-beam single-step exposure [6], and employing a single diffraction element such as a photomask [7]. In terms of fabrication utilizing either direct holographic interference exposure or indirect photomask exposure, the period of H-PDLC gratings is always constant. It has been reported that a H-PDLC reflection grating with varied period can be fabricated by using interference between two diverging beams that was generated by two lenses [22]. For a transmission 2D grating with gradually varied periods, a special photomask is required. Since the period cannot be easily adjusted using one photomask, several required photomasks have to be prepared. Even though it has

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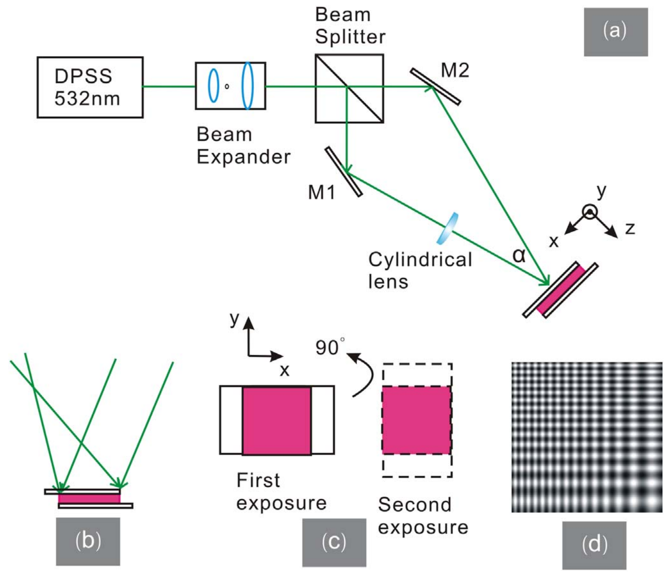

Fig. 1. (a) Schematic experimental setup for fabrication of a 2D H-PDLC grating with a variable period. The laser beam was expanded and divided into two coherent beams with diameters of 16 mm. (b) Magnified view of varied intersection angles on the sample surface to show why the grating period varies on a single substrate. (c) Schematic to show how the sample rotates during dual exposure. (d) Simulated interference pattern showing the varying period within 2D H-PDLC grating.

been reported that a cylindrically concave Lloyd's mirror can be used to fabricate a 2D grating with variable period on silicon substrate by lithography technology [23], research results on a switchable 2D H-PDLC grating have been rarely reported.

In this paper, we report on a simple method to fabricate 2D H-PDLC gratings with varied periods by inserting a refractive cylindrical lens in a conventional double interference optical path, which varies the incident angle of one of the two interference laser beams on the exposure surface. This 2D grating was fabricated by rotating the sample by 90° counterclockwise after the first horizontal exposure and then performing the second vertical exposure. The prepared 2D H-PDLC grating exhibits varied periods on the whole sample with square symmetry in one of diagonal directions, but with rectangular asymmetry in off-diagonal direction. In addition, for each point on the grating, the diffraction efficiency and transmission efficiency can be adjusted by changing the applied driving voltage. When several gratings with different periods are required, the proposed single 2D grating with a variable period can replace them and reduce the size of device. Additionally, the grating with a constant period can be used for lasing emission; so the proposed grating characterized by monotonically varying periods could be used in a tunable multi-wavelength organic laser. Specifically, the wavelength of the emission laser depends closely on the period of embedded grating, thus a tunable laser can be possibly obtained from one single dye-doped sample.

2. Materials and methods

The starting LC/prepolymer mixture syrup used was consisted of 44.71 wt% acrylic monomer (ebecryl 8301 acrylated urethane) from UCB, Inc., 34.76 wt% nematic LC (TEB50) from Beijing Tsinghua Yawang Liquid Crystal Material Co., Ltd., 9.94 wt% surfactant (S-271) from Chem Service, Inc., and 9.94 wt% cross-linking monomer (1-Vinyl-2-pyrrolidinone), 0.15 wt% photoinitiator (Rose Bengal), 0.4 wt % coinitiator (N-phenylglycine), all from Sigma-Aldrich, Inc. Additionally, 0.05 wt% Ag nanoparticles from Beijing Nachen S & T Ltd. were added to improve optic-electric characteristics of H-PDLC grating [24]. The TEB50 nematic LC used has an ordinary refractive index of $n_o = 1.524$ and a birefringence of $\Delta n = 0.1896$. The dielectric anisotropy of the LC is $\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} = 11.5$, where $\varepsilon_{\parallel} = 17.3$. The acrylic monomer has a refractive index of 1.49. We chose TEB50 nematic LC due to the close match of its refractive index with that of the prepolymer used in our experiment. The combination can be used to fabricate a H-PDLC grating with high performance that has been previously reported [24]. Additionally, a surfactant was used for reducing surface tension of the prepolymer and decreasing the driving voltage of the grating. The cross-linking monomer can reduce the size of the LC molecule and increase the diffraction efficiency of the grating. The combination of the photoinitiator and coinitiator results in an absorption peak of 560 nm that is close to the recording wavelength of 532 nm. Thus, they can improve the sensitivity and absorption of the PDLC material to the recording laser beam. The mixture should be kept

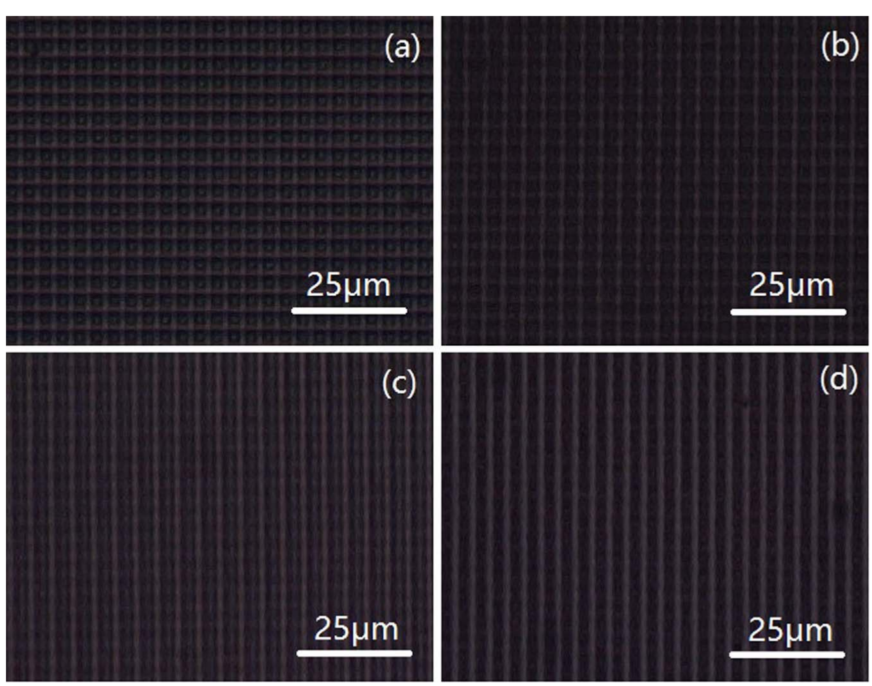

Fig. 2. Ordinary microscope image of 2D H-PDLC grating under different exposure time rates (first time/second time): (a) 2 s/60 s, (b) 5 s/60 s, (c) 7 s/60 s, and (d) 10 s/60 s.