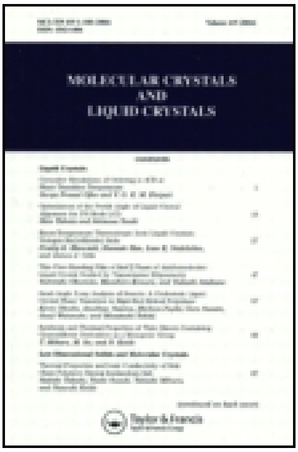

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Optofluidic Microstructures Containing Liquid Crystals

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Optofluidic Microstructures Containing Liquid Crystals

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We report our recent efforts on the realization and characterization of a conductive polydimethylsiloxane (PDMS) microstructure containing liquid crystals (LC). The sample has been realized by means of a "layer" by "layer" strategy. An indium tin oxide (ITO) layer has been sputtered on PDMS by utilizing thermal evaporation technique; an inter-diffusive scenario, leading to the embedding of the ITO layers within the PDMS matrix, makes the structure conductive and still morphologically homogeneous, even after mechanical stretching and deformation are applied to the sample. Then, the microstructure has been functionalized with an amorphous film of SiO_x, infiltrated with an anisotropic and reconfigurable fluid (nematic liquid crystal, NLC) and characterized in terms of morphological, optical and electro-optical properties.

Keywords Liquid crystals; optofluidic devices; flexible substrates

Introduction

With a variety of potential applications, micro/nanotechnology and micro/nanoscience represent a key technology for future, rapidly leading to fundamental step-forwards towards the realization of new devices and systems, in order to reach a high manufacturing standard. Ranging from extensions of conventional devices to development of new materials with dimension on the micro/nano scale, technology research could particularly concern flexible electronic devices, which are expected to rapidly transform areas such as communications, energy and displays [1]. Progress in flexible technology allows us to imagine a large number of innovative products such as electronic papers, smart gloves and so on.

E-papers are one of the most cited examples, as well as thin-film electronics for liquid-crystal displays (LCDs). However, although many important systems have been already developed, the production of high-performance flexible devices incorporating liquid crystals (LCs) remains a challenge. In fact, integration of LCs with elastic substrates can hardly be exploited, because of the associated difficulties in uniformly aligning LCs on plastic or flexible substrates during the manufacturing process [2]. Recently, among several

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elastomeric materials, Polydimethylsiloxane (PDMS) has attracted significant attention due to its high optical quality, cast-molding capabilities and low surface energy [3], with numerous applications in microfluidics and optofluidics [4]. Patterning metallic structures is popular in microelectronics, but metals cannot adhere strongly to PDMS due to the low surface energy of the insulating PDMS. This represents a critical point [5], especially for current technological developments [6], such as display oriented applications, which require electrodes for signal control and detection [7].

The basic idea, reported recently, is to make elastomers conductive by depositing metallic structures on them; this enables obtaining flexible electronic substrates, which can behave as an active control of the visual colour [8]. A critical point is represented by the choice of the optimal process for depositing the conductive material; this process has to avoid cracking of layered structure when it is subjected to mechanical stretch or deformation. Attempts to address this issue by patterning conductive indium tin oxide (ITO) on PDMS have been reported, but results are affected by the presence of crack lines in the realized structures [9]. In this framework, we have developed a new process for the realization of a conductive and functionalized PDMS microstructure containing well aligned nematic liquid crystal (NLC). The optical and electro-optical properties of the composite structure, based on the birefringence [10] property of the NLC, have been also investigated.

Fabrication Process

In a first step, a PDMS grating has been fabricated by direct electron beam lithography on SU8 (Vistec EBPG5000, 100 kV acceleration voltage, at a dose of 5 μCb/cm^2) and subsequent pattern transfer to PDMS via conventional cast molding. The grating period was 2 μm and its thickness approximately 1.5 μm. To overcome the insulating behavior of the PDMS, we realized a conductive ITO layer on the microstructure. The ITO layer deposition was carried out by a standard DC-sputtering physical vapour deposition (PVD) [11] process from an ITO target, in Ar atmosphere; in a second step, hard baking of the whole sample enabled stabilizing the structure.

Figure 1a is a scanning electron microscopy (SEM) view of the microstructure after the sputtering of the ITO layer; it confirms the presence of a strong adhesion between ITO and PDMS and the absence of any crack line, even after mechanical stretching and deformations are applied to the sample. Indeed, the polymeric PDMS morphology ensures a high permeability to several, different, materials thanks to its porous nature [12]; thus the ITO layer is uniformly embedded into PDMS surface and becomes able to undergo stretching and deformations.

The ITO/PDMS bilayer was then functionalized with a SiO_x thin film [13]: in this way, we obtained a SiO film, deposited on the ITO/PDMS microstructure with an angle of 60° with respect to the normal of the sample inducing a thickness of about 30 nm.

Figure 1b is SEM view of the layered structure after PVD thermal evaporation of SiO_x: the adhesion between the ITO layer and the PDMS surface still remains, even in presence of the evaporated SiO_x film and after stretching/deformation experiments. In the final step, we sandwiched the NLC between the realized SiO_x/ITO/PDMS microstructure and an ITO covered glass, where a SiO_x layer has been deposited as well. Figure 1c is a sketch and Figure 1d is a picture of the realized electro-conductive PDMS sample.

Optical Characterization

We have realized a typical optical setup for the transmitted intensity measurement, in which a He-Ne laser is the source of a single-mode radiation at the wavelength $\lambda = 633$ nm. The laser beam impinges on the sample at normal incidence, after passing through a polarizer and a $\lambda/2$ half wave plate. The transmitted intensity is analyzed by a photodiode, whose output signal is sent to an oscilloscope; this measures a voltage that is proportional to the transmitted light beam power. We have analyzed the behavior of the diffracted intensity when varying the impinging light polarization direction (Fig. 2a).

In order to investigate the NLC alignment, we performed optical experiments by using the probe setup already described in [14]. We monitored (Fig. 2a) the first order diffraction efficiency value versus the polarization angle of the impinging probe radiation (He-Ne laser, $\lambda = 633$ nm). Probe light polarized orthogonal to the grating stripes (p polarization) experiences a high index contrast (n_e-n_{pdms}~0.3) while light polarized along the grating stripes (s polarization) experiences a low index contrast (n_o-n_{pdms}~0.1); here, we have indicated with n_e, n_o, the extraordinary and ordinary refraction index of the NLC respectively, while n_{pdms} is the refractive index of the PDMS material. We stress that the optical selectivity (Fig. 2a) exhibited by the sample enables an immediate visualization of the good alignment of the NLC inside our optofluidic structure.

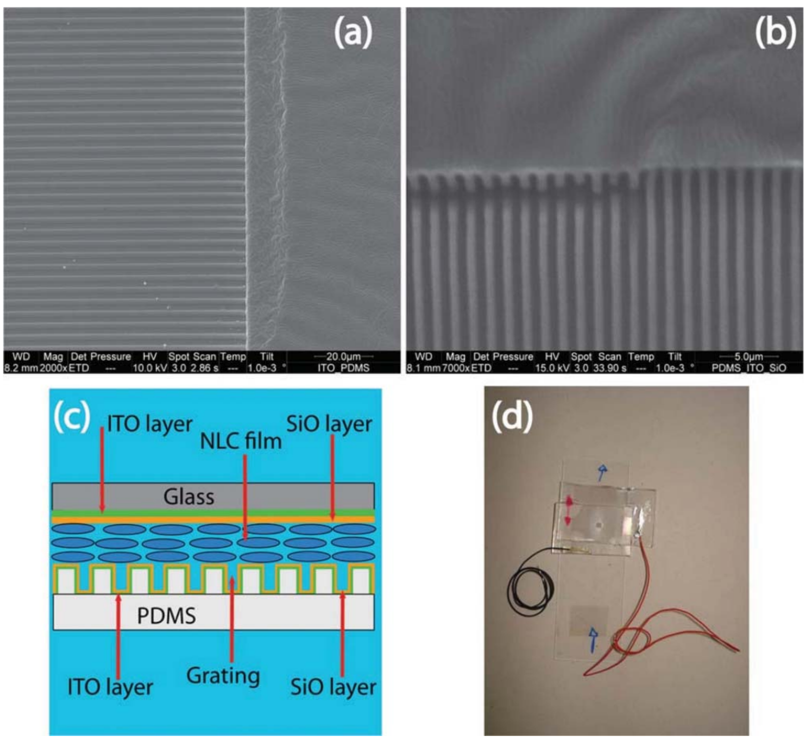

Figure 1. SEM view of the ITO sputtered PDMS microstructure (**a**). SEM view of the microstructure after evaporating SiO_x on the ITO layer (**b**). Sketch of the NLC configuration (**c**) in the aligning, electro-conductive, PDMS cell (**d**).

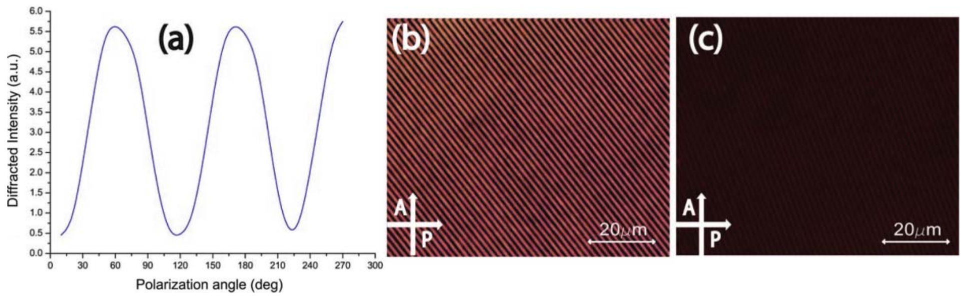

Figure 2. Behavior of the diffracted intensity plotted as a function of rotation angle of the half-wave plate (**a**). Polarized optical microscope (POM) pictures acquired during rotating the structure ((b) and (c)).

The diffraction efficiency of a periodic structure is strongly related to the index contrast [15]; so that, the high contrast ratio reported in Fig. 2a confirms that NLC is very well aligned as suggested by POM view of Fig. 2b–c. In fact, by rotating the sample between crossed polarizers, it is possible to observe a strong optical contrast (better that 20:1) between the bright and dark states.

Electro-Optical Characterization

We performed an electro-optical characterization by placing the sample between crossed polarizers, with the NLC director axis placed at 45° with respect to the polarizers/analyzer axes, and monitoring the transmitted intensity of a monochromatic light source (He-Ne laser, $\lambda = 633$ nm) while applying an a.c. external voltage (square wave, 1 kHz).

The sinusoidal like behavior reported in Fig. 3a (yellow curve) is the typical optical response [16] of uniformly aligned birefringent materials under external electric field (green curve), described by:

$$T_{\perp} = \sin^2 \frac{(\pi d \Delta n(E, T, \lambda)}{\lambda} \tag{1}$$

Here, $T_{\perp}$ is the transmittivity of light through crossed polarizers, d is the cell thickness and Δn the birefringence, which depends on the presence of external fields (E), on the sample temperature T and on the probe wavelength λ. In pure birefringent samples, under the

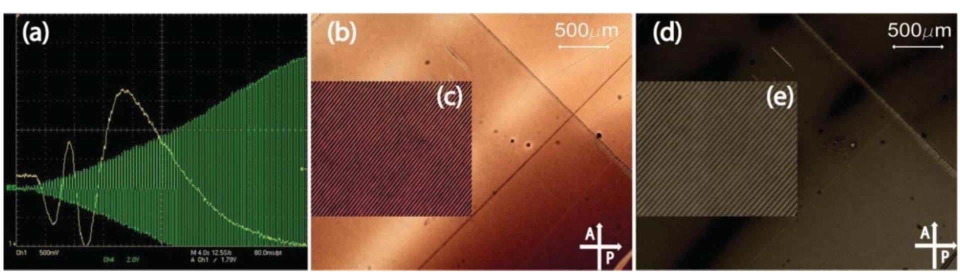

Figure 3. Electro-optical (**a**) response of the sample: temporal response (yellow curve) in presence of external applied voltage (green curve). Polarized optical microscope (POM) pictures of the micro structure, acquired by applying a voltage ((**b**) and (**d**), with their high magnifications (**c**) (**e**)).

influence of an applied electric field, the NLC director reorients along the field direction, thus changing the effective birefringence of the sample and modulating the transmitted intensity, according to Eq. (1). We monitored the temporal evolution of the transmitted intensity (Fig. 3a, yellow curve) by applying a square wave electric field, whose amplitude has been increased from 0 V/μm to 4 V/μm (Fig. 3a, green curve). We completed the investigation by acquiring a POM view of the microstructure with (Fig. 3b) and without (Fig. 3d) the presence of the applied voltage. It is worth noting that the optical contrast of the structure can be switched from bright (high magnification Fig. 3c) to dark state (high magnification Fig. 3e). The behavior confirms the good characteristics of our electro-conductive PDMS device, which demonstrates, in this way, its suitability to be profitably utilized for a fast production of a grey/colour scale in display applications.

Conclusions

In conclusion, we have reported on the fabrication and characterization of an electro-switchable structure realized on a flexible PDMS substrate containing a well aligned NLC. In order to realize the flexible switchable sample, we sputtered a thin layer of ITO on the PDMS substrate; diffusion process leads to the embedding of the ITO layer within the PDMS matrix, ensuring a uniform and regular morphology of the sample also after testing with mechanical stretching and deformations. In a second step, the sample has been evaporated with a film of SiO_x for inducing planar alignment of the NLC director. In order to characterize the structure in terms of a switchable device, we performed a series of optical and elecro-optical experiments. We believe fabrication of a similar device can be easily extended on a large area for realizing a new generation of flexible displays with performances comparable to, or even better than, standard LCD screens.

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