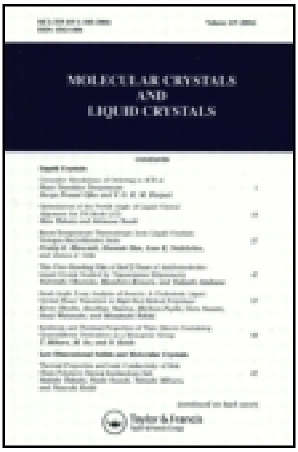

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General Purpose Soft Template for Photonic Applications: From All-Optical to Electrical Reconfigurability

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In this paper we report on the realization and characterization of a polymer template sculptured in photosensitive material on a chemical inert surface, devoted to micro/nano-confinement of a wide range of organic components, with self-arrangement properties at the nanoscale. The high quality morphology of the polymeric micropattern arrays is obtained by combining a nano-precision level optical holographic setup and a multi-step chemico-physical process. The general purpose template represents the basic platform to be filled with different soft composite materials: Due to their self organization capabilities, light responsive Liquid Crystals (LC) and short pitch Cholesteric LC have been investigated.

Keywords Liquid crystals; Diffraction gratings; Holography

Introduction

Self-organization and template driven organization represent the two main routes followed by complex systems to order their basic constituents. A well known example of an organic system that can follow both routes is represented by liquid crystals (LCs). These materials combine self-organizing properties with fluidity, and can fulfill conditions imposed from outside. Because LCs are liquid, their molecular order is sensitive to environment, e.g. temperature, electric and magnetic fields, or adsorption of chemicals [1]. On the other hand, nano-science and nanotechnologies enable innovative capabilities of artificial materials, by exploiting either the intrinsic properties of sub-units and/or the collective properties of the material. The possibility of combing periodic, aperiodic and random nanostructures with LCs represents, therefore, one of the leading topics of today's photonics research [2]. Furthermore, structures realized on the surface of semiconductors, dielectrics or polymers can represent a passive platform for LC confinement and alignment; depending on the control of specific physical parameters of materials and structure morphology, innovative devices like micro-lasers [3], optical storage devices [4] and bio-sensors [5] have been realized.

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A key functionality necessary for realizing integrated photonic systems is the tuning and/or switching capabilities, combined with intrinsic physical properties of the soft-composite element. Results obtained in this field in the last decade show that combination of several different materials with hololithographic techniques have been extensively investigated and exploited [6]. In this framework, realization of POlymer LIquid Crystal Polymer Holograms Electrically Manageable (POLIPHEM) [7] and POlymer LIquid CRYstal Polymer Slices (POLICRYPS) has a prominent position for the technological innovation of the fabrication process, the sharp morphology of the realized samples and their photonic properties [8]. POLICRYPS is a composite micro/nano hetero-structure made of slices of almost pure polymer alternated to films of well aligned Nematic Liquid Crystal (NLC). It is obtained by irradiating a homogeneous syrup of NLC, monomer and curing agent molecules with an interference pattern of UV/visible light, under suitable physical and geometrical conditions [9]. The curing process is carried out at a nano-precision level by exploiting an "ad hoc" designed optical holographic setup [10], which enables the spatial periodicity of the structure to be easily varied from few hundreds of nanometers to the tens microns. Structures exhibit a high degree of stability both from chemical and mechanical points of view. POLICRYPS has proven an excellent candidate to become a passive matrix for photonic applications, due to the following characteristics:

- A high quality morphology, thanks to the high stability of the optical holographic setup used for the fabrication;
- Absence of LC droplets inside the structure;
- Excellent glass to glass optical bond and very good solvent resistance, thanks to the adhesive (NOA 61 by Norland) used in the initial mixture.

In this paper, we show that starting from the POLICRYPS morphology, realization of an optically active multi-purpose template for a wide range of photonic applications can be carried out.

POLICRYPS as passive template

The wet etching process of the POLICRYPS is carried out by dipping the sample (without opening the cell) in a water solution of tetrahydrofuran (THF). Then, by capillary flow, the solvent washes out the LC from the polymeric structure. For short time intervals (3–4 h), the THF acts as a selective agent, removing the LC and the unpolymerized component without affecting the regularity of polymer slices (Fig. 1a). Removing of LC from the sample is accelerated by vibrating the system at ultrasonic frequencies. The process is carried out above the Nematic-Isotropic transition temperature of the LC (65°C), to ensure a low viscosity of the LC component.

A first investigation of the "empty template" has been carried out by observing the black area of Fig. 1a between parallel polarizers (Fig. 1b) with a high magnification objective (50x): the sample appears as made of sharp polymer slices separated by empty channels. Peculiar capabilities of the "empty POLICRYPS" template have been investigated through the observation of self-organization processes in different LC phases: i) Nematics, for grating realization purposes, ii) cholesterics, for optical activity features.

All-Optical Gratings

One of the most exciting developments in LC science and technology is the possibility of using light, instead of electric signals, to control the behaviour of the material. Photonic

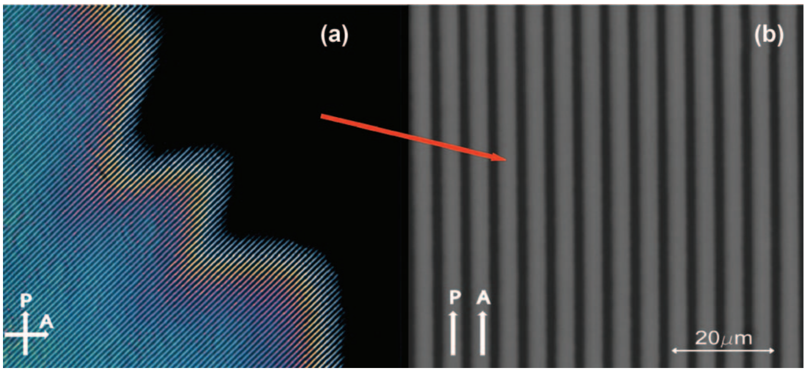

Figure 1. POM view of the POLICRYPS structure during the micro-fluidic etching process (a). Polymer template after removing the NLC (b).

circuits, where beams of light redirect the flow of other beams of light, are a long-standing goal for developing highly integrated optical communication components [11]. For this kind of application, we have used a NLC doped with CPND-57 (by BEAM Engineering), a high performance, photosensitive LC [12]. The "empty POLICRYPS" template has been filled by capillary with CPND-57 in the isotropic phase (65°C). After the filling process has been carried out, the system was cooled down to room temperature, with a cooling rate of 0.5 deg/min.

Figure 2a is a POM view of the obtained sample, which highlights its good optical quality. By using the pump-probe optical setup described in details in ref [13], an-optical control of the diffracted light intensity can be obtained. The best performance has been exhibited by a sample of thickness L = 6.93 μm, with a pitch $\Lambda = 1.52$ μm; according to Kogelnik's model [14], the grating is characterized by a Bragg parameter $\rho = \Lambda^2/\lambda L = 0.52$ which indicates that the grating operates in the Bragg regime (volume grating). Figure 2b shows a sharp variation of the diffracted beam intensity driven by a sequence of On-Off irradiance with a pump green light. When the structure is excited by the pump beam, NLC molecules become disordered, due to a light induced trans-cis photoisomerization process [15], and the probe light experiences an average refractive index; this is very close to the one

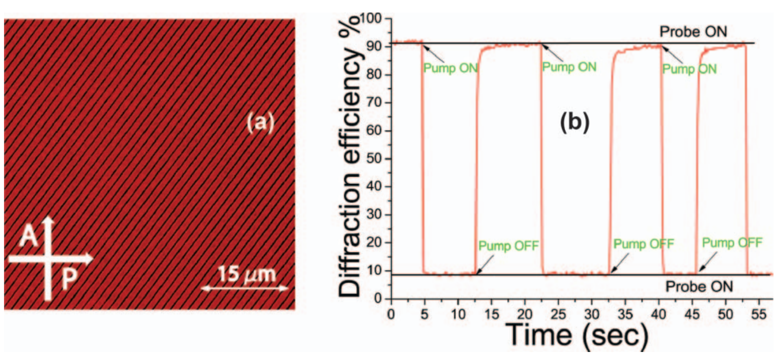

Figure 2. POM view of the template filled with light sensitive NLC (a). Optical response of the sample (red curve) triggered with a sequence of On-Off pump beam (b).

of the polymer slices, thus causing a noticeable decrease of the diffraction efficiency. When the pump light is switched off, a cis-trans photoisomerization of the azo-NLC molecules takes place, which induces a re-orientation of the NLC director; a high modulation of the refractive index is restored and a high diffraction efficiency state is thus re-established. Devices that exhibit such features are of great interest in the optical engineering field and can enable fabrication of a new generation of components with low-power and high-contrast optical switching capability, at telecommunication wavelengths.

ULH Configuration

Cholesteric Liquid Crystals (CLCs) are LCs possessing a helical super-structure. They organize in layers with no positional order within each layer, but characterized by a director axis, whose orientation smoothly changes from layer to layer; the reorientation of the director axis tends to be helicoidal, with a pitch that can vary in the range 0.1–20 μm. A further, in-plane rotation of the helical axis can be obtained by applying an electric field across the cholesteric film, a phenomenon reported by Meyer [16] and named "flexo-electric effect." LC devices based on this effect require a warm up voltage to maintain a Uniform Lying Helix (ULH) configuration, where the helical axis is uniformly aligned in the plane of the two confining substrates. An interesting consequence of the flexo-electric effect is the so called "chiral-electro-optic effect" (FEO), which is an in-plane rotation of the optical axis under the action of an electric field, observed when a short pitch cholesteric is aligned in a ULH texture [17]. FEO is of remarkable interest for applications, being temperature independent, with response times that are in the microsecond range. In order to induce the ULH configuration with a short pitch CLC, we have used a polymer micro-channel method, based on the exploitation of the already described "empty POLICRYPS" structure. The template has been filled by capillary with a short pitch CLC (BL088 by Merck, helix pitch $\sim$400 nm). The sample was kept at a fixed high temperature ($\sim$90°C) during the whole filling process, thus allowing the liquid-crystalline component to remain in the isotropic phase. By slowly cooling down the sample to room temperature (0.5 deg/min), a self-organization process occurs, owing to the Isotropic-Chiral liquid crystal phase transition: The system tends to minimize its free energy by orienting the LC helices in a ULH geometry. Sample features have been investigated by means of electro-optical experiments, through a probe setup [18]. In order to optimize the structure characteristics, a sample thickness of 10 μm has been used, which maximized the light transmission [14]; in this experimental condition, indeed, a diffraction efficiency of less than 7–8% has been measured.

Here we want to stress the capability of our template to align the CLC in a ULH texture: Fig. 3a is a POM micrograph of the sample at the edge of the photo-sculptured grating area, which shows, on the left, the existence of a standard focal conic texture, due to the random distribution of the helical axes. On the right, the ULH geometry induced by the structure is well evident. We have performed an electro-optical characterization on the area depicted in Fig. 3 a (right view). An external electric field (square wave, 1 Khz, Fig. 3 b), applied across the cell perpendicularly to the helix, induces an in-plane tilt of the optical axis of the short pitch cholesteric, aligned in a ULH texture and the tilt is inverted if the polarity of the electric field is reversed; The magnitude of the transmitted intensity (green curve, Fig. 3b), which is related to the tilt of the optical axis [18], is proportional to the applied electric field. In fact, the applied field induces an in-plane rotation of the sample optical axis; consequently, the light transmitted through the sample is modulated, according to equations reported in [19]. The response is linear with the field at moderate applied fields (6.3 V/μm, in our case) with characteristic times that fall in the microsecond range.

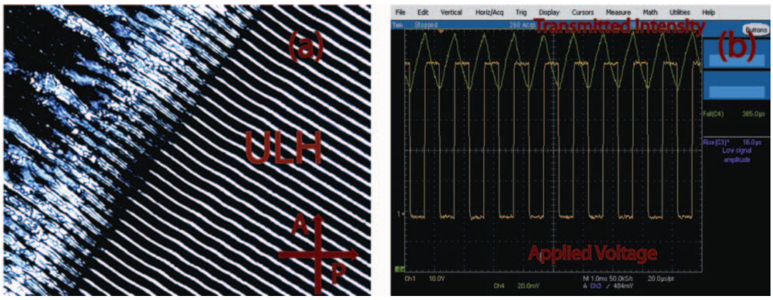

Figure 3. POM view of the template filled with short pitch CLC at the edge of the grating area (a); its electro-optical response is reported in (b).

Liquid crystal devices exploiting this effect represent a new prospective for future technologies, since common LC devices exhibit response times which are 1 order of magnitude longer.

Conclusions

In conclusion, we have reported on the realization of a periodic soft-composite template with a wide range of photonic applications. The innovative procedure makes the "empty POLICRYPS" template really versatile. In fact, the universality and the simplicity of exploitating the new polymeric structure is demonstrated by the easy overcoming of some standard and well known LCs drawbacks. In general, in order to exploit the extraordinary properties of LCs for electrooptical and/or photonic applications, chemical and/or mechanical treatment of the containing surfaces represents a crucial and almost phenomenological need, which is related, case by case, to the particular kind of application and depends on the specific kind of used LCs (nematic or cholesteric). In our case, by using only one kind of material and one fabrication procedure, we can align and microconfine in a single step a large variety of liquid crystalline materials without the need of any kind of surface chemistry and/or treatment.

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