Chapter 6. Applications of CLC photonic crystals

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1. Flexible reflective display and dynamic reflector

Traditional liquid crystal displays use color filters to generate colors. However, only ~33% of light passes the color filter and only ~40% of light passes the polarizers. It leads to a transmission rate of light as low as 4~9%. For applications in portable displays, power consumption becomes a major issue. Therefore, color reflective displays have great potential in the portable display market due to their characteristic advantages, including selective reflections and low cost operation. Usually CLCs will go through three stages in response to the increasing external voltage (V). At V=0, the LC directors are planar aligned and Bragg reflection is established so that it shows selective reflection band. As the voltage increases, the LC directors turn into a focal conic texture which is a strong scattering mode, where the chiral structure is strongly disturbed into a random distribution due to the competition of electric force and anchoring force. Under high voltage driven, the electric force dominates so that it becomes homeotropic texture. Figure 1 depicts the LC distribution indifferent textures.

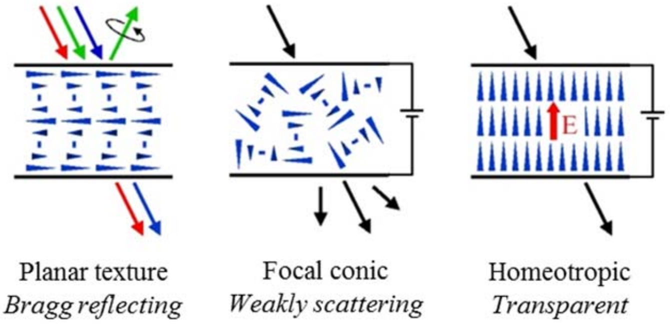

Figure 1 – Cholesteric liquid crystal under voltage driving at planar texture (V=0), focal conic texture ($V>V_{th}$) and homeotropic texture (high V).

Based on electro-optic properties of CLCs, reflective displays have developed radically since the 1990s; they can provide bistable displays for use indoors and outdoors of low and high resolution. Typically, they reflect about 30–40% of the incident light of a specific waveband but can be made into multilayer displays capable of showing full-color images. And they can be made on rigid and flexible substrates. Several display companies including Kodak, Kent Display, HP and Philips, have been developed bistable CLC reflective display. As shown in Figure 2, Fujitsu developed the world's first monochromatic and full color flexible CLC displays in 2006. The key to Fujitsu's CLC display is a film substrate that's sufficiently flexible to allow the paper to be bent, but rugged enough to prevent the image from distorting. And the CLC based display was required very small amounts of energy for changing the image. They have been used for electronic book applications due to the advantages of bistability, reflectivity, flexibility and low power consumption. In particular, encapsulated CLCs can be used to make flexible displays by a roll-to-roll process.

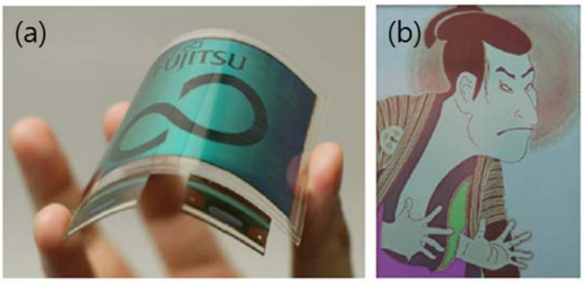

Figure 2 – Photograph of (a) one-layer and (b) three-layer flexible cholesteric display (Courtesy of Fujitsu, http://www.theregister.co.uk/2005/07/13/fujitsu_epaper/)

In addition, the unique and potentially widely applicable dynamic color changes observed in CLCs have been developed since 1990's. The use of CLCs as stimuli responsive optical materials has been developed for dynamic color tuning or switching in Figure 3. These effects include large wavelength shifts, autonomous on–off operation, high sensitivity, responsiveness to a variety of external stimuli, and controllable tuning rates. These materials offer many potential advantages over other dynamic color systems especially in their simple fabrication and in some cases, very sensitive response. Dynamic color tuning or switching by thermal, electric, and photon stimuli are useful for a range of applications, including displays, lasing, data communication, novelty optics, or toys. For more detail on dynamic color tuning, please refer to a review for dynamic color tuning or switching in stimuli-responsive CLC systems by T. J. White et al.

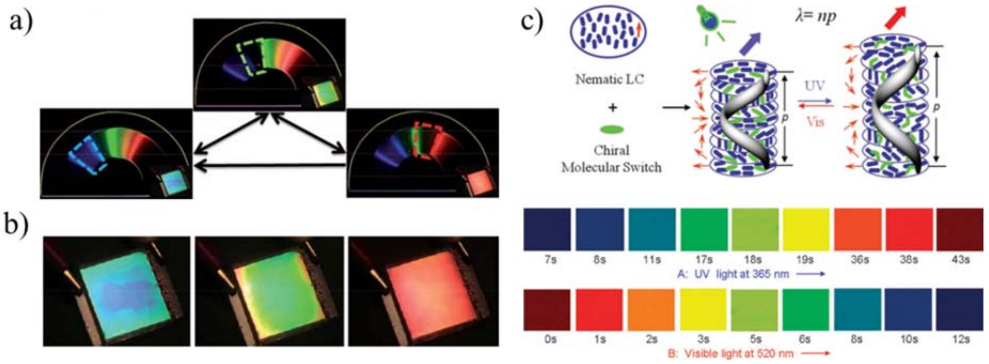

Figure 3 – Photograph of Illustration of switchable and tunable CLC reflectors by a) thermal, b) electric, and c) photon stimuli.

4-3-2 Laser

CLC structure forms a one-dimensional (1D) photonic crystal. Like an energy gap for electrons propagating in periodic crystal structures, a stop band emerges at the edges in CLC. When light propagates in periodic media with the same periodicity as the light wavelength, the light suffers reflection due to the photonic bandgap (PBG). Hence, if CLC is doped with dyes, emitted light within the PBG is confined and amplified in CLC, and finally lasing results. This type of cavity without using mirror is called distributed feedback (DFB) cavity used for DFB lasing. Dowling et al. predicted that DFB lasing occurs at the edge of PBG of 1D periodic structures with sufficiently large refractive index modulation. Since CLCs themselves spontaneously form DFB cavity, this is the simplest microlaser structure Figure 4. The refractive indices in CLC change due to the helical structure of the dielectric ellipsoid. It is a great advantage of CLC microlasers compared with conventional semiconductor lasers, in which the fabrication of microstructure is necessary.

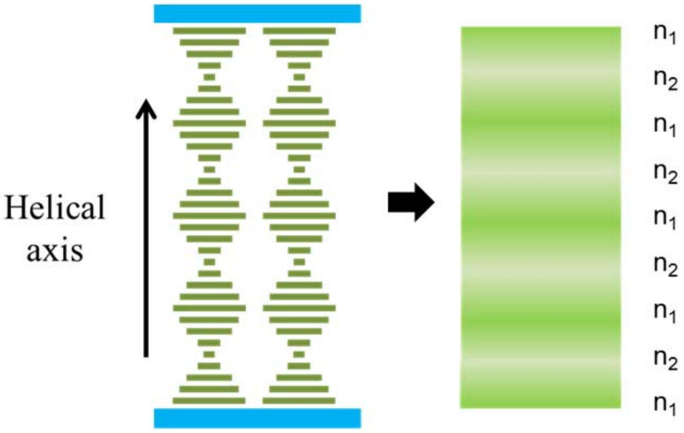

Figure 4 – Cholesteric liquid crystal planar structure with helical axis perpendicular to substrates. Schematic 1D-PBG structures with sufficiently large refractive index modulation.

Recently, Humar and Muševič have demonstrated for the first time 3D- or omnidirectional laser by placing a 15–50-µm-diameter microdroplet of CLC doped with a laser dye. Dispersing the CLC microdroplet in an immiscible fluid such as glycerol allowed it to spontaneously self-assemble into an aspherical shape because of surface tension. Then, the formation of 3D helical structure with radial helical axes could be shown in Figure 5. Strong periodic modulation of the refractive index caused the formation of a multilayered spherical Bragg resonator. This microresonator can be thought of as hundreds of concentric shells of alternating refractive index.

Although lasing condition is the same as that in 1D-CLC lasers and lasing wavelength is uniquely defined by the helical pitch, an important point is that the light emitted at the center is confined three dimensionally due to the radial helical axes; thus omnidirectional lasing emission occurs toward all the radial direction.

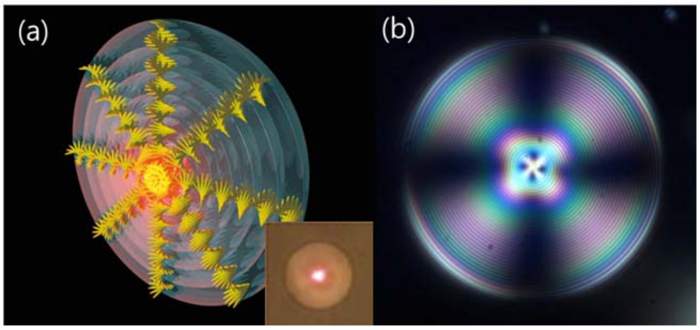

Figure 5 – (a) Helical liquid-crystal structures self-assemble inside a CLC microdroplet, (b) creating concentric shells of constant refractive index that form a dielectric structure known as a Bragg-onion optical microcavity. This 3D laser emits omnidirectional light.

The soft matter nature of these materials and their response to external stimuli lead to tuning feasibilities from near ultraviolet through visible to near infrared. The broad wavelength tuning range of CLC lasers, coupled with their microscopic size, narrow line width (< 0.1 nm) and high optical efficiency as compared with more conventional solid-state lasers, could open up new possibilities for labs-on-a-chip, medical diagnostics, dermatology, spectrum analysis, laser arrays, and holography.

Actually, there are several types of CLC microlasers. In this chapter, we only described band edge laser (or distributed feedback laser). For more detail on several lasing modes, please refer to a review by Kopp et al.

3 Micor- Nanopatterning using CLCs

Tunable and self-assembled structures as lithography masks have attracted considerable attention in recent years due to their cost-effectiveness combined with versatility and simplicity, for the fabrication of structures spanning length scales from a few nanometers to several micrometers. Recently, the photomask based on smectic LC defects shows light-focusing abilities by creating a graded refractive index that refracts and focuses incident light similar to a lens. CLC with periodic helical twist of molecular orientation have been used for a long time as materials capable of pronounced Bragg diffraction effects. Thus, CLCs have been reported for a "tunable" mask to fabricate defined and integrated patterns on photoresists (PR) over large areas. It is demonstrated that under an applied electric field, the CLC attains a texture known as the fingerprint texture, with its helical axis in the plane of the sample. This fingerprint texture acts as a set of ordered array of cylindrical lenses that generates a periodic light intensity (phase grating), which is then used to expose the PR, thus imprinting a pattern that faithfully follows the intensity distribution produced by the CLC, Figure 6. In addition, it is possible to use the fingerprint texture of a CLC as a polarization-selective photomask for the preparation of periodic line patterns based on intrinsic optical anisotropy of LC molecules. The fabrication of a CLC mask is very fast and simple, thus the technique is cost-effective and versatile due to the tunablity of the CLC structure, such as by controlling the length-scale of the pitch either by increasing the concentration of the chiral dopant or by using electric fields. The approach based on CLCs has significant advantages over existing methods to micro- and nanopatterning applications, including easy fabrication, the creation of long-range surface ordering, very rapid formation of periodic arrays, and the ability to generate various feature sizes.

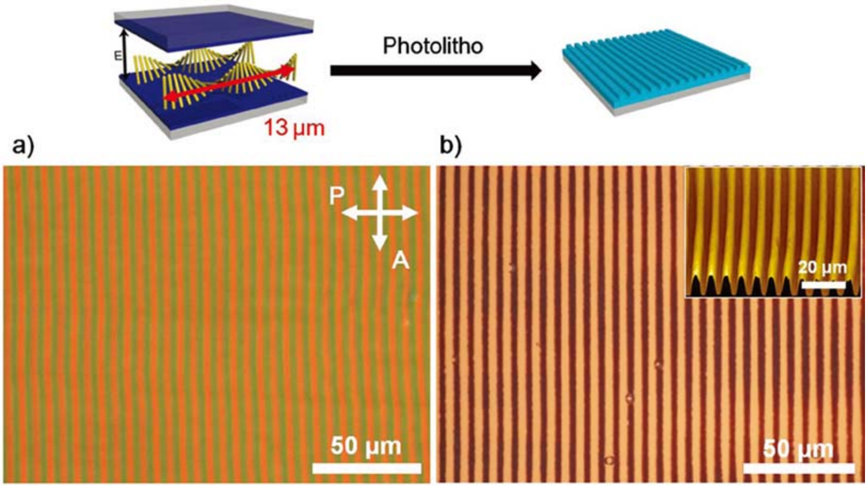

Figure 6 –Fabrication of a line pattern on a photoresist (PR) by CLC photomask. a) POM image of the fingerprint texture obtained upon application of an electric field. b) OM image of the developed pattern on the PR, where the inset shows an AFM topography of the patterns.