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Review

A review of the fabrication of photonic band gap materials based on cholesteric liquid crystals

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ABSTRACT

Cholesteric liquid crystals (CLCs) are known to exhibit selective reflection of incident radiation due to their periodic helical structure, which makes them promising candidates for a myriad of different photonic applications. At normal incidence, CLCs reflect circularly polarized incident light of the same handedness as the cholesteric helix and of wavelength λ between n_oP and n_eP, where n_o and n_e are the ordinary and extraordinary refractive indices, respectively, of the locally uniaxial structure, and P is the pitch of the helix. Thus, the reflection bandwidth $\Delta\lambda$ is given by $\Delta\lambda = \Delta nP$, where the birefringence $\Delta n = n_e - n_o$. Within the bandwidth, right-circularly polarized light is reflected by a right-handed helix, whereas left-circularly polarized light is transmitted. Outside the bandwidth, both polarization states are transmitted. Therefore, $\Delta\lambda$ depends on Δn. Moreover, Δn is typically limited to 0.3–0.4 for colorless organic compounds, and $\Delta\lambda$ is often <100 nm in the visible spectrum. Although a narrow reflection band is desirable for applications such as optical filters and thermal imaging, it also becomes a drawback in their applications, such as reflective displays, broadband circular polarizers and switchable mirrors. The purpose of this review is to take a closer look into how to broaden the reflection band in CLCs to overcome the above limitations for a wide variety of applications. This review covers the methodology that was used until recently, when the fabrication of photonic band gap (PBG) materials arose, based on CLCs. The mechanisms for broadening the reflection band have been reviewed.

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1. Introduction

1.1. Photonic crystals

Photonic crystals (PCs) are periodic dielectric structures that can be used to prohibit, confine or control light propagation in a specific wavelength band (known as the photonic bandgap). Photonic crystals are optical media that contain a periodic distribution of high and low refractive indices in 1, 2, or 3 dimensions. When the periodicity is commensurate with the wavelength of visible light, they exhibit photonic band gaps (PBGs) in this spectral region, where the propagation of light is prohibited within a range of “forbidden” frequencies. These periodic dielectric thin films can be utilized to confine, manipulate, prohibit the transmission of, and steer photons, allowing their integration as a foundational element of all-optical integrated circuits. Photonic crystals have attracted a large amount of attention in recent years owing to their complex, periodic dielectric nanostructures, which offer unique optical properties, and their ability to control the flow of light [1–3].

Photonic crystals (PCs) that have a three-dimensional (3D) ordered structure with a periodicity of the optical wavelength have attracted considerable attention from both fundamental and practical points of view because in such materials, novel physical concepts such as the photonic band gap (PBG) have been theoretically predicted, and various applications of photonic crystals have been proposed [4–6]. More specifically, the study of stimulated emission in the PBG is one of the most attractive subjects because in the band gap, a spontaneous emission is inhibited and low-threshold lasers based on photonic crystals is expected [7–9].

1.2. Photonic liquid crystals

A PC is a periodic structure that modulates the refractive index at the scale $s \approx \lambda$. The structure is designed to form “photonic bandgaps” (i.e., a range of wave vectors at which light cannot propagate) (1). To provide the full bandgap in all directions, the PC should be 3D, which represents a challenge. In addition, the PC is often required to have structural defects, such as points (to trap light) or dislocations (to guide light). One of the approaches is the self-assembly of small particles, typically spheres, from water solutions into 3D colloidal crystals.

In LCs, the small rod-like molecules are free to move around as in a regular fluid, but they remain locally parallel to one another, thus establishing an orientational order along a nonpolar axis $n = -n$ called the director. In the simplest case of the so-called “nematic” LC, there is no other type of long-range order, and ñ is the optic axis. Because of the anisotropy of dielectric permittivity at low and high (optical) frequencies, the nematic LCs are widely used as tunable component infiltrating PCs [10–12] and metamaterials (MMs) [13]. The degree and direction of the orientational order of the nematic filler can be controlled by a variety of means (temperature, pressure, and electromagnetic fields), thus allowing one to tune the PC and MM hosts dynamically. In addition to the simple nematic structure, the rich world of LCs offers phases with spatial modulation of density and molecular orientation, periodic in one (smectics and cholesterics), two (columnar phases), or three (blue and cubic phases) dimensions. The period is often in the range of 10 nm to 1 μm, relative to the PCs and MMs.

It is also anticipated that the use of liquid crystals (LCs) might enable the tunability of the photonic crystals because LCs can exhibit optical anisotropy. Their refractive indices can be changed by controlling the direction of the molecules or the temperature. The properties of the LCs can also be changed by a transition between the liquid crystal phase and the isotropic phase or between the different types of LC phases. A practical scheme for tuning the band structure using LCs has recently been proposed, and electrically and thermally tunable photonic band gap composites have already been reported [14–25]. However, in most cases, the changes in the optical stop band were not large, and complete switching has yet to be realized.

1.3. Photonic crystals based on chiral/cholesteric liquid crystals

Photonic crystals (PCs) with an ordered periodic structure at the optical wavelength scale have attracted a large amount of interest from both fundamental studies and practical applications [26–28]. One of the important forms of PCs is cholesteric liquid crystals (CLCs) that spontaneously form periodic helical structures, which leads to selective reflection for circularly polarized light [29–35]. Thus, CLC can be regarded as a one-dimensional photonic crystal (1D PC) for the specific circular polarization of light and is stable for some photonic applications, such as color filters [36,37], reflective displays [38,39], and low-threshold laser devices [40–44]. Cholesteric liquid crystals (CLCs) possess a helical structure and exhibit two stable states at a zero field: in the focal conic texture, they scatter light in forward directions, whereas in the planar texture, they reflect circularly polarized light with the same handedness as the helical axis. In CLCs, the period of the helicoidal structure is equal to half the pitch p, and for light that propagates along the helical axes, $p = \lambda_0 \times n$, where λ_0 is the wavelength of the maximum reflection or the middle of the selective reflection band, and n is the average refractive index $n = (n_e + n_o)/2$. The extraordinary and ordinary indices of refraction are denoted by n_e and n_o, respectively. The photonic bandgap (PBG) width of a conventional CLC is equal to $p \times \Delta n$ and is proportional to the anisotropy of the refractive indices $\Delta n = n_e - n_o$. Within the bandwidth, right-circularly polarized light is reflected by a right-handed helix, whereas left-circularly polarized light is transmitted. Outside the bandwidth, both polarization states are transmitted. Tuning the PBG characteristics of CLC, such as tuning λ_0 in the visible or infrared spectrum, increases the PBG width or increases the reflected light flux, which is attractive for many applications in reflective displays, polarizers and color filters [45–54].