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Eelectro-optic Behavior of Opal-LC Photonic Crystals

Daeseung Kang

Abstract

In this paper, we describe the electro-optic effects of photonic crystals made of a synthetic opal filled with a nematic liquid crystal(LC). By applying an external electric field, a shift in the Bragg reflection peak position(stop band) and a field-induced change in its peak reflectivity are observed. These significant surface alignment effects of the opal-LC composite are discussed in a similar manner for Freederick-type transitions of LC within a confined geometry in the presence of external fields.

Keywords : photonic crystal, liquid crystal, photonic band gap, bragg reflection, electro optic, opal

1. Introduction

In recent years, photonic crystals, artificially engineered periodic dielectric structures, have attracted considerable attention due to their capabilities to produce photonic band gap(PBG)[1,2], in which the propagation of electromagnetic radiation is prohibited. It is now known that a self assembly of colloidal silica spheres produces closed packed FCC(face centered cubic) opals[3], and that FCC structures with high dielectric contrast exhibit 3D PBG between the 8th and 9th bands. Of particular interest is the generation of tunable 3D PBG materials that enable one to manipulate the spectral properties of PBGs, by utilizing external fields such as electric field, temperature, mechanical stress, or chemical composition[4~6]. Liquid crystals(LCs), in this regard, are very efficient in achieving the tunability because it is easy for LCs to manipulate in effective refractive index with a small electric field, and the incorporation of liquid crystals into 2-D and 3-D PBG composite structures has begun to be explored[4, 7~9]. Although opal itself cannot provide PBG properties, however it presents useful information such as Bragg peak shift, and tunable stop band. Furthermore the complicated confined structure made by interstitial voids is a good model system for investigating confinement effect of liquid crystals.

In this paper, we present an experimental study of the structure and electro-optic behavior of hybrid liquid crystal-silica sphere photonic crystals, formed by filling the(26 % by volume) void space of synthetic FCC opals with nematic liquid crystal. In fact, we found a significant surface alignment effect: an electric field-induced shift in the Bragg reflection peak position and field-induced change in its peak reflectivity was observed.

2. Experiments

In the experiment, the face-centered cubic(FCC) colloidal photonic crystals were made from amorphous silica(SiO_2) spheres whose nominal diameter D was 200 nm. We used commercially available silica particles from Nissan Chemical, and to ensure sufficient monodiespersity, a fractionation process of repeated centrifugation and dilution was utilized. Crystal growth was carried out

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Corresponding Author : Daeseung Kang
Department of Electrical Engineering, Soongsil University 1-1, Sangdo-Dong, Dongjak-Gu, Seoul 156-743, Korea.
E-mail : dkang@ssu.ac.kr **Tel** : +2 820-0642 **Fax** : +2 817-7961

by slow sedimentation in water in a 10μm thick gap between vertical indium-tin oxide(ITO) coated glass plates. The crystals grew with the [111] direction normal to the plates at a rate of ~1mm/day. Crystal rigidity was enhanced by sintering for 12 hours at 250 °C after slow evaporation of the water at lower temperature. FCC structure was confirmed by scanning electron microscopy(SEM) of the dehydrated crystal with the glass removed(Fig. 1). The nematic LC PCH5 was then filled into the void space of the opal via capillarity in vacuum in the isotropic phase. PCH5 was uniaxially birefringent, with ordinary and extraordinary refractive indices, n_o = 1.49 and n_e = 1.62 at 25 °C, respectively.

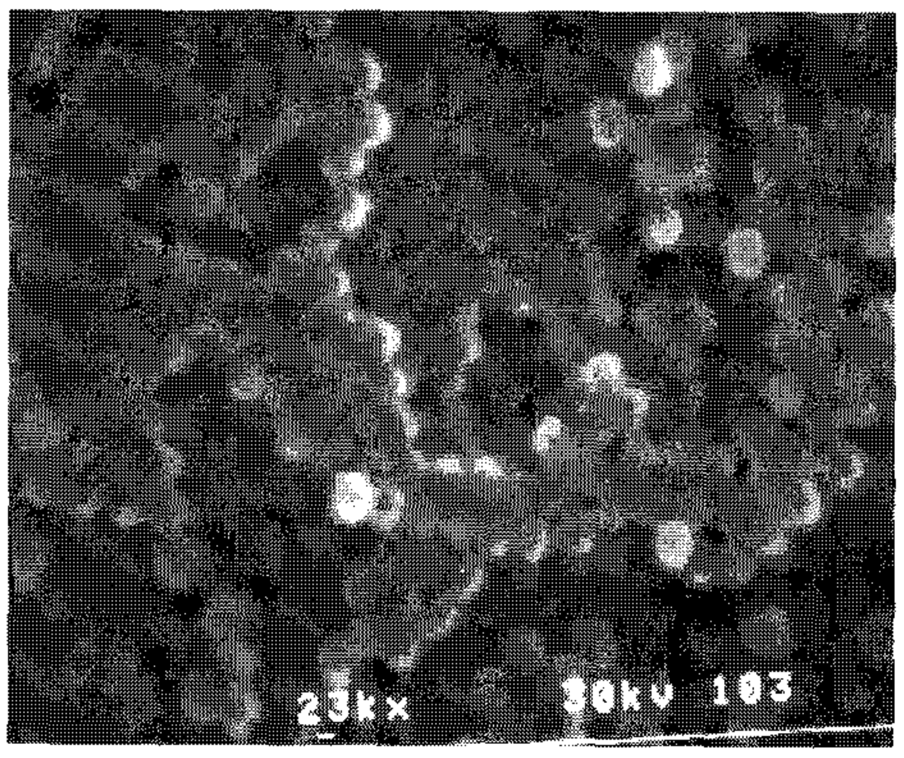

Fig. 1. SEM micrograph of a closed packed fcc opal.

Optical characteristics of the opals and of the opal/LC composites were studied using Bragg reflection microscopy. The FCC crystal domains were of dimensions 50 – 100 μm in the plane of the plates. The FCC crystals were viewed at normal incidence to the plates in the [111] Bragg back-reflection, expected at wavelength

$$\lambda_B = D(2\sqrt{2/3})\,n \ , \qquad (1)$$

where we assume contact between the nearest neighbors and n is the effective mean refractive index.

3. Results and Discussions

Fig. 2 shows the Bragg peak along [111] for T = 45 °C. The peak maintains its basic shape with both electric field application and temperature change, indicative of a bulk crystal effect, i.e. an effective LC refractive index variation. Fig. 3 shows the field dependence of the Bragg wavelength, λ_B. Assuming that the Bragg peak wavelength shift is caused by variation of mean refractive index of the medium, n,

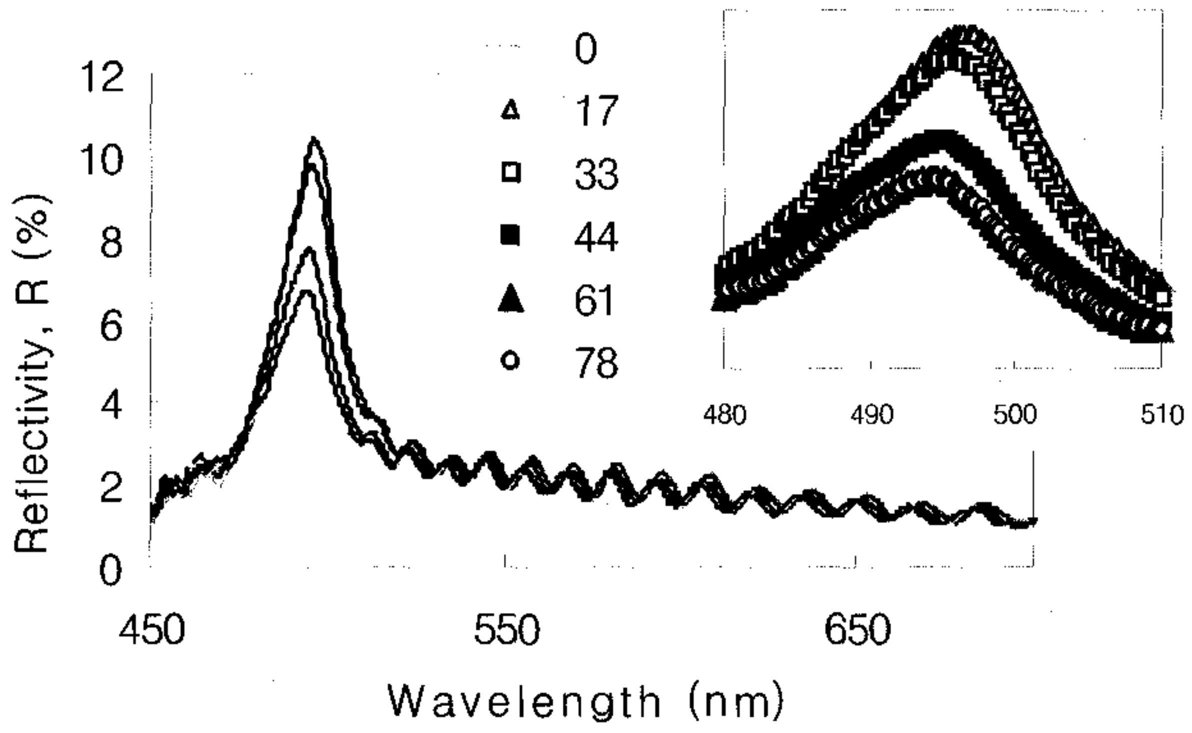

Fig. 2. Reflection spectra of an opal crystal infiltrated with PCH5 for light incident parallel to [111] direction, showing a field-induced shift of the [111] Bragg reflection peak.

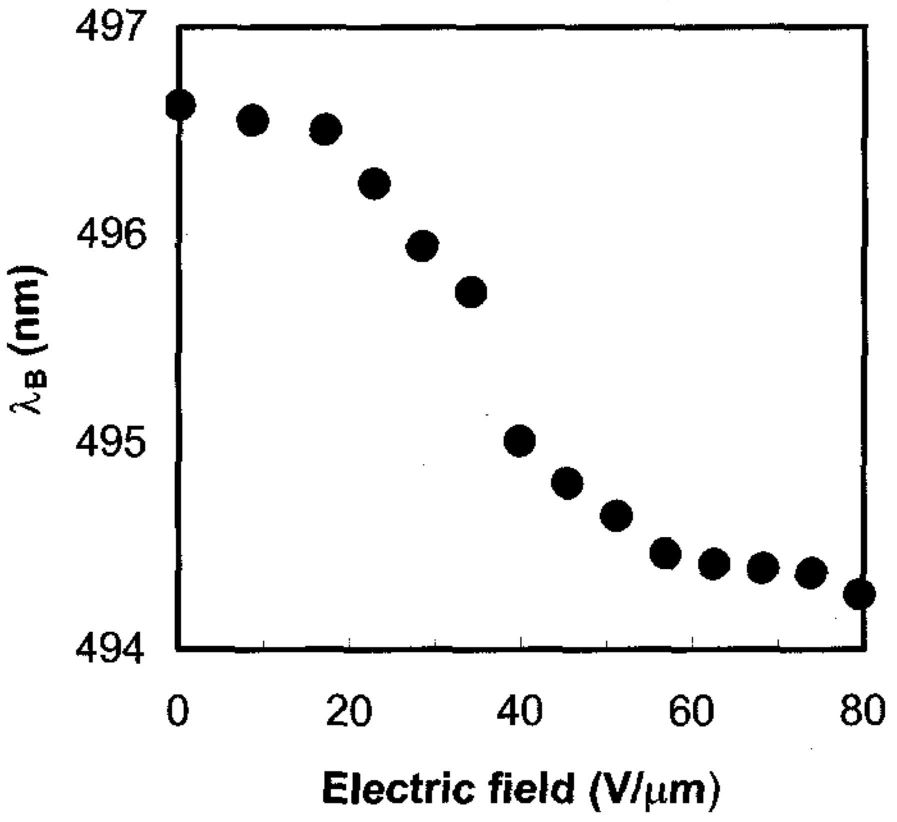

Fig. 3. Field dependence of Bragg reflection peak wavelength.

$$n = \sqrt{0.74n_s^2 + 0.26_{\mathrm{L\,Cell}}^2} \qquad (2)$$

the peak wavelength shift can then be related to mean LC refractive index change using an effective medium model. In Eq. (2), n_s, and n_{LCeff} represent refractive index of silica and the effective refractive index of LC, respectively. Then, the corresponding Bragg wavelength is

$$\lambda_B = D(2\sqrt{2/3})\sqrt{0.74n_s^2 + 0.26_{\mathrm{L\,Cell}}^2} \qquad (3)$$

Where, n_s is fixed at its typical bulk value n_s = 1.45, and, in order for n_{LCeff} to match the bulk LC value n_{LC} = 1.52 in the isotropic phase at T = 55 °C, D is fixed at D = 207 nm, well within the range of specified particle size. Since $n_{\mathrm{LCeff}} > n_s$, the LC – opal refractive index contrast increases monotonically with n_{LCeff}, such that the field induced reduction in n_{LCeff} is accompanied by a decrease of λ_B, as plotted in Fig. 3. By increasing the external electric field strength, the reflection peak position undergoes Freedericksz-like transition.

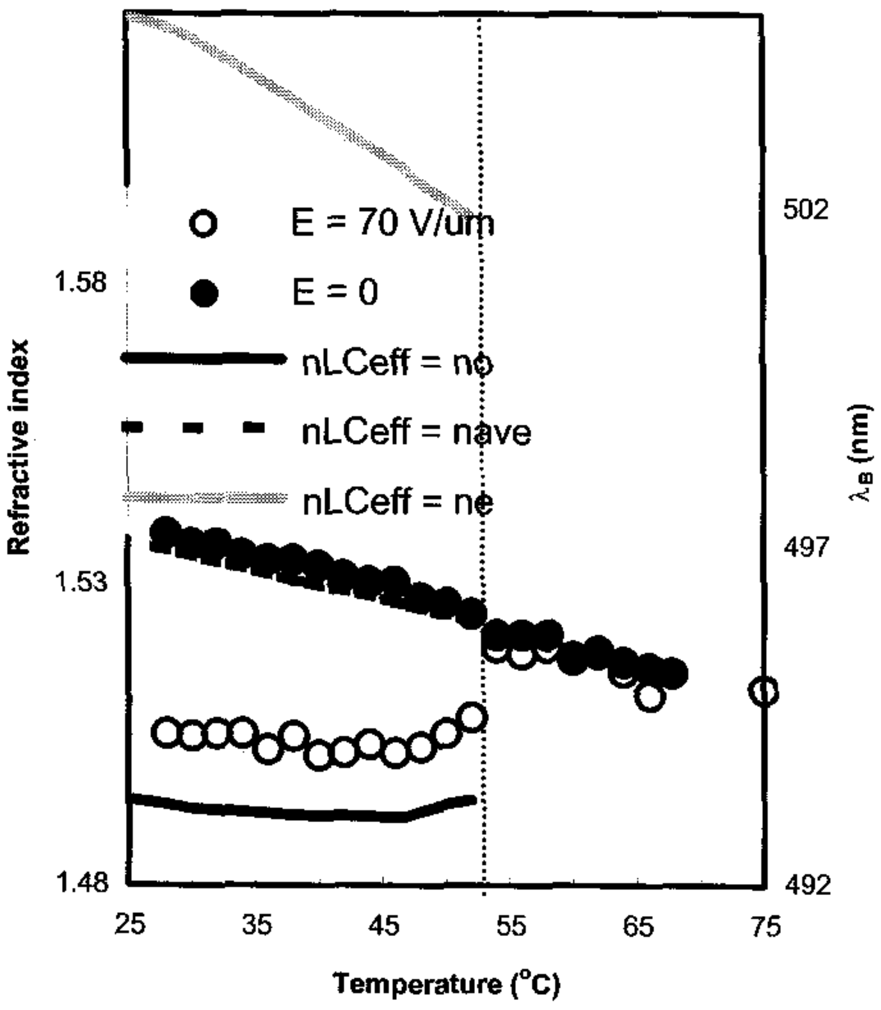

Fig. 4. Bragg reflection peak wavelength λ_B and the corresponding effective LC refractive index n_{LCeff} vs temperature. The solid line curves show the maximum possible range of λ_B and n_{LCeff}, as the LC index varies from its minimum value n_o to its maximum value, n_e, and a dotted line curve represents n_{ave}, the mean bulk LC refractive index. The vertical line separates isotropic (higher temperature) and nematic phases of PCH-5.

Fig. 4 shows the thermal and field-induced behavior of the [111] Bragg wavelength and the corresponding effective LC refractive index n_{Lceff}. With these values n_{LCeff} calculated from λ_B matches the bulk LC index in the isotropic temperature range, and follows the isotropic average of the bulk nematic indices

$$\mathrm{n}_{\mathrm{ave}} = \sqrt{\left(n_e{}^2 + 2n_o{}^2\right)/3} \qquad (4)$$

in the nematic temperature range. This is an expected result for an isotropic $\mathbf{n}(\mathbf{r})$ distribution in the limit that the opal – LC index difference is sufficiently small that there is only weak spatial inhomogeneity of the optical electric field in the opal/LC lattice. Fig. 4 also shows the Bragg wavelengths in extreme cases such that the effective LC index has its maximum(n_e) and minimum (n_o) values. These limits represent the maximum possible field-induced excursion of λ_B in this composite system. Fig. 4 also shows the temperature dependence of λ_B with a 70 V/μm, 60 Hz AC electric field applied to the composite. As shown in Fig.4, the applied field generates a distinct change in λ_B, producing ~60 % of the maximum possible shift of n_{LCeff} toward n_o. This indicates that $\mathbf{n}(\mathbf{r})$ is reoriented parallel to $\mathbf{E}$ and normal to the ITO plates, as expected for the positive dielectric anisotropy of PCH5($\Delta\varepsilon = 12.7$)[10]. The optical electric field is then mostly normal to $\mathbf{n}(\mathbf{r})$ so n_{LCeff} approaches n_o.

4. Conclusions

Significant shift of Bragg reflection peak caused by electric field-induced change of effective refractive index of a nematic LC is observed in an opal-LC composite photonic crystal. LC molecules within the voids of silica spheres are randomly arranged, and collectively respond to the external electric field, giving rise to about 60 % change in the shift of Bragg reflection peak. The incomplete reorientation of molecules indicates that the strong anchoring of silica surface plays an important role in forming a topological defect structures inside the void space of silica spheres. In summary, this experiment shows feasibility that tunable photonic band gap structures could be easily achieved by utilizing a nematic LC into synthetic opal crystals.

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