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RESEARCH ARTICLE

Reflective spectrum broadened by nano-particle-network in chiral liquid crystals

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Abstract Based on the analytical expression of the electromagnetic field solution of a helical symmetric dielectric material, the relationship between spectral reflectivity and birefringence of a chiral liquid crystal and the blue shift of the Bragg reflection in the condition of oblique incidence are presented in this paper. The theoretical results indicated that: 1) If birefringence (Δn) of the liquid crystal is greater than 0.2 and the thickness of the liquid crystal layer reaches 3μm, the liquid crystal layer will reflect more than 90% of the incident light; 2) To reflect the whole visible spectrum by Bragg reflection, Δn of the liquid crystals in plane alignment state should exceed 0.6; 3) When the incident beam inclines to 60° from the normal direction, the blue shift of the reflective spectrum will reach to 100 nm. On the other hand, since the Δn of the commercial chiral liquid crystals is not larger than 0.2, to get the entire visible reflective spectrum, it needs to introduce a polymer network into the liquid crystals and make a sagging structure on the surface of substrates. The contribution of the network is to establish random anchorage that makes the pitch varied, hence broadening the Bragg reflection spectra. The random distribution of the sagging structure on the surface substrate is used to induce random screw axes of the chiral liquid crystal, which not only causes a blue shift of Bragg reflection but also further stretches the reflection spectra. Experiments demonstrated that the Bragg reflection spectrum could be broadened from 80 nm to more than 120 nm, and the contrast reaches 4:1 by introducing both polymer network and sagging structure on the substrate surface cell.

Keywords reflective spectrum, chiral liquid crystal, cholesteric, nano-particle-network

1 Introduction

Bistable effect and Bragg reflection are well-known effects of chiral liquid crystals, and the effects have been used to make Zero Field Bistable LCDs (ZFB-LCDs), which were applied in electronic maps, e-book displays, and so on [1]. The main advantage of ZFB-LCDs is that the displays use power only in the refreshing moment, not in the display time. When ZFB-LCDs are applied for the device for large information displays like e-books, these two advantages are obvious: first, because of low average dissipation, the battery can last quite a long time. In fact, two AAA batteries could supply enough power for the e-book to be read for 3 months; second, as the display works when page turning happens, while it does not work for the rest of time, the display has quite a long life.

Such display works in Bragg reflection mode, which reflects light in a relatively small spectrum range, so, the displays are colored. Both calculations and experiments show that while the birefringence Δn of liquid crystal is small, reflectivity is obviously different because of the variety of the wavelength. Therefore, it is impossible to get a white background display.

Adding dense nano-particle-network into the chiral liquid crystal is the currently used method to broaden the spectral range, as patents and articles have been declared [2,3]. However, these methods brought some problems: the existing dense nano-particle-network in the liquid crystal will separate the interior of the liquid crystal into many domains, and the interface of the domains scatter incident light even in focal conic state. Accordingly, reflectivity in the black state will be increased and result in an inferior contrast ratio.

Reflective wavelength spectrum is related to birefringence Δn of liquid crystals. A larger Δn results in a wider range of the wavelength. If Δn is greater than a certain magnitude, and the optical pitch of the chiral liquid crystal equals to the mid-value of the visible wavelength,

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a chiral liquid crystal in planar state can realize the whole visible light spectrum reflection.

For practical applications, the following two phenomena were considered to be applied in ZFB-LCDs: One is the relation of Δn and the thickness of the liquid crystal layer with reflectance in the visible spectrum, and the pitch length varies randomly in different domains. We should know the optimal dimension of the domains. Another is the blue shift of the reflective spectrum related with screw axes departure from the vertical position caused by the mountainous surfaces. The research of these two aspects may achieve the ZFB-LCD in a wide range of spectral reflectance with high-contrast. Two aspects above will be discussed to obtain the condition of broadening reflective spectral range in visible light.

2 Reflectivity in oblique incidence

Both theories and experiments have demonstrated that chiral liquid crystal in the planar state reflects rotary polarized light. Right-handed chiral liquid crystal reflects left-handed polarization light while it transmits right-handed polarized light, and vice versa. In normal incidence condition, the central reflective wavelength λ_0 equals to the optical pitch $\bar{n}\cdot p_0$. Herein, $\bar{n}$ is referred to as the average refractive index and p_0 is the pitch of the chiral liquid crystal.

The range of reflective wavelength depends on birefringence Δn. The value of reflectivity η depends on the thickness of the chiral liquid crystal layer. According to the derivation by B. Priestley [4], reflectivity in normal incidence is expressed as

$$\eta = 1 - \exp\left(-\frac{4\pi\sigma\bar{n}d_0}{\lambda_0}\right), \tag{1}$$

where σ is defined as

$$\sigma = \sqrt{\sqrt{4\left(\frac{\lambda_0}{\bar{n}p_0}\right)^2 + \left(\frac{n_{//}^2 - n_{\perp}^2}{n_{//}^2 + n_{\perp}^2}\right)^2} - 1 - \left(\frac{\lambda_0}{\bar{n}p_0}\right)^2}, \tag{2}$$

and $\bar{n}$ is defined as

$$\bar{n} = \sqrt{\frac{n_{//}^2 + n_{\perp}^2}{2}}, \tag{3}$$

wherein $n_{//}$ is the extraordinary refractive index and $n_{\perp}$ is the ordinary refractive index.

When the ray tilted irradiates to the chiral liquid crystal in the planar state, Bragg reflection occurs. Because of $\lambda_0 = \bar{n}p_0$, we should consider the pitch length, which is referred to as the equivalent pitch, that is, the pitch length projected along the ray, as shown in Fig. 1.

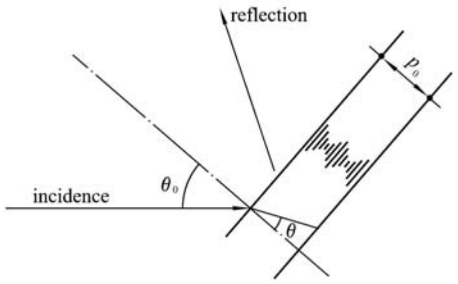


Fig. 1 Modification of refractive angle and equivalent pitch in chiral liquid crystal

From the equation $\sin\theta = \frac{\sin\theta_0}{\bar{n}}$ we can get $p = p_0\cos\theta$, that is $p = p_0\sqrt{1 - \frac{\sin^2\theta_0}{\bar{n}^2}}$.

Therefore, the central reflective wavelength in tilted incidence can be described as

$$\lambda_\theta = \bar{n}p = \bar{n}p_0\sqrt{1 - \frac{\sin^2\theta_0}{\bar{n}^2}} = \lambda_0\sqrt{1 - \frac{\sin^2\theta_0}{\bar{n}^2}}. \tag{4}$$

The formula above is equivalent with that created by N. Moriya [5]:

$$\lambda_\theta = \lambda_0\cdot\cos\left[\sin^{-1}\left(\frac{\sin\theta_0}{\bar{n}}\right)\right]. \tag{5}$$

3 Results

The optical pitch of the liquid crystal $\bar{n}p_0$ considered here was fixed to 0.6 μm, thickness of the liquid crystal layer was 3 μm and the ordinary refractive index was 1.520. When birefringence (Δn) of the chiral liquid crystals varied from 0.1 to 0.6, results of the calculation according to Eq. (1) is shown in Fig. 2.

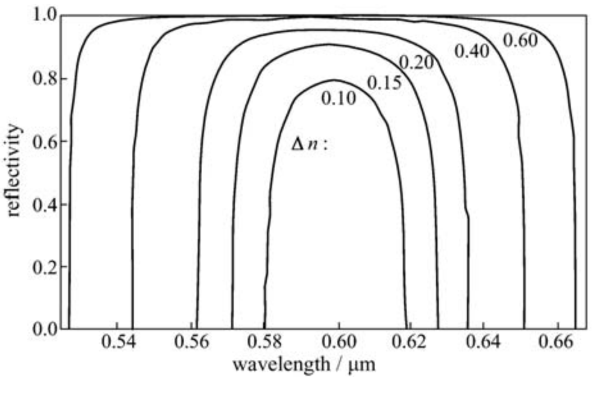


Fig. 2 Relationship between reflectivity of chiral liquid crystal and wavelength

It is seen that the reflectance of a liquid crystal depends mainly on its Δn. When Δn reaches 0.6, uniform spectra reflection will occur for the whole visible light. However, the Δn of commercial chiral liquid crystal is only 0.2, though the Δn of alkyne liquid crystals can achieve up to 0.4. Therefore, it is impossible to obtain the reflection in the whole visible spectral range by commercial liquid crystals in the traditional structure. In Fig. 2, it can be seen that when Δn reaches 0.2, and the thickness of the liquid crystal layer exceeds 3 μm, reflectance reaches more than 90% at the central reflective wavelength. Therefore, it is possible to anchor the liquid crystal in small domains to change its pitch by polymer network anchoring. Because the liquid crystal will be anchored on the polymer network, the anchoring function makes the pitch vary in different domains along the thickness. According to the results above, the optimal dimension of the domains should be 3 μm.

On the other hand, to get the relation between the reflective wavelength of a chiral liquid crystal in planar state and incident angle, we changed watch angle from 0° to 60°, and the central spectrum of reflection from long wavelength to short wavelength. It was referred to as blue shift. The optical pitch of the chiral liquid crystal is 0.6 μm and the refractive index of ordinary light is 1.520. According to Eq. (4), central reflective wavelength varies along the incident angle, which is shown in Fig. 3.

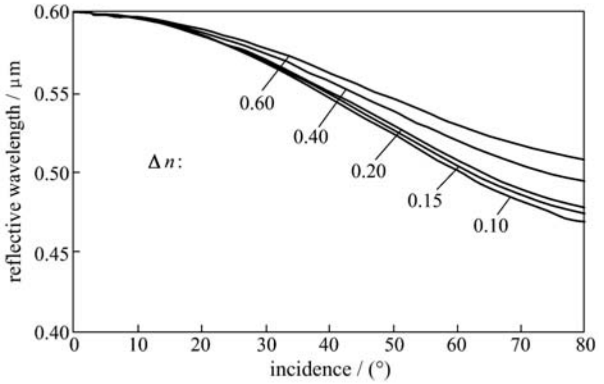


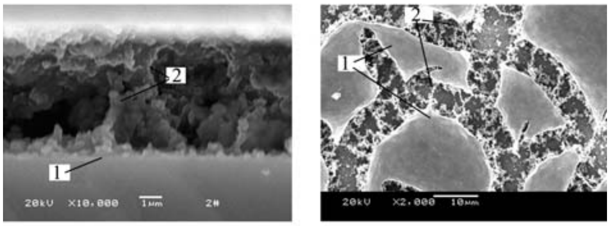
Fig. 3 Blue shifting of center reflective wavelength along incident angle

The increase of incident angle reduces the length of projection of the optical pitch along the ray, thus central reflective wavelength decreases remarkably. It can be seen that the smaller the birefringence is, the more remarkable the blue shift of the reflective wavelength is. When incident angle reaches 60°, and the blue shift reaches 100 nm, when Δn equals to 0.2. The reflectance spectrum width is 80 nm, and the range of the maximum visible spectrum is 300 nm. If a diffused illuminant would be adopted, we would see good reflection of most of the spectral range in visible spectrum. Vice versa, if a method could be found to make the axes of chiral liquid crystals randomly tilted from one place to another, by color mixed in eyes, a homogeneous reflection in most of the visible spectrum would be realized by spotlighting.

Adding the polymer network into a liquid crystal (so-called polymer network-stabilized chiral liquid crystal) is the way to vary the pitch, while introducing the mountainous boundary structure on the inner part of the substrates is the way to introduce the randomly distributed blue shift. Because the pitch length is varied randomly by the polymer network, and pitch axis randomly varies along the thickness direction of the cell, the Bragg reflectance spectrum was expanded. Combining the polymer network with the mountainous roughness on glass substrates, which tilts the axes of the chiral liquid crystal, the Bragg reflectance spectrum expands further.

Therefore, besides the preparation of the polymer network in liquid crystal, a polymer film needs to be deposited by phase separation process in the internal surfaces of the liquid crystal cell. After a strong voltage pulse, a cholesteric liquid crystal has no pure planar state; instead, it presents the state close to the planar state, referred to as "pseudo-planar state". In microcosmic view, the pitch length in displasy should be diverse everywhere, plus the direction of axes should be randomly tilted in the cell. Hence, the center wavelength of the Bragg reflection differs in position, the combination color on the display is exhibited. Because all the reflective color is mixed, the reflected light spectrum broadens. Similarly, after a low voltage impulse, it presents a "false focal conic state." Experiments show that the transmitting property is not obviously changed.

Figure 4 is the morphology of a ZFB-LCD by SEM. Fig. 4(a) shows the mountainous boundary near the surface, and Fig. 4(b) shows the polymer network, in which the liquid crystal had been extracted by hexane.



(a) (b)

Fig. 4 SEM of polymer residue. (a) Mountainous boundary near the surface; (b) polymer network

In Fig. 4, 1 is polymer deposited on the boundary, and 2 is the sparse polymer network. According to the analysis above, it can be seen that the action of the network is to establish a random distributed anchoring mechanism, which resulted in the variation of pitch along the position. To introduce a random reflective spectrum, the mountainous boundary is employed to induce random oblique axes distribution to use the random blue shift of the reflective spectrum at randomly distributed positions. In the combination structure, a homogeneous spectra reflection is realized in most of the visible spectrum. According to the preparation process and quantity of polymer, polymer was divided into the surface part and the network part. Depending on the process, the range of Bragg reflective wavelength varied from 80 nm to more than 120 nm, with the contrast being kept around 4:1. The samples are shown in Fig. 5.


(a) (b)

Fig. 5 ZFB-LCD by combination of surface deposited polymer and polymer network. (a) ZFB-LCD in glass substrates; (b) ZFB-LCD in PETs

4 Conclusions

To realize the homogeneous reflection of ZFB-LCD in the whole spectral range, the birefringence of a chiral liquid crystal should be more than 0.6. The increase of incidence angle leads to the blue shift of the reflective wavelength. However, the birefringence of commercial liquid crystal is only 0.2. To realize a homogeneous reflection in most of the spectral range, pitch length perturbation by polymer network should be utilized, plus the utilization of a mountainous zigzag structure on the surface, which tilts the axes of chiral liquid crystal. By combining surface pattern and polymer network, uniformity reflection in the visible spectrum will be realized and the corresponding Bragg reflection spectral range will increase up to 120 nm with the contrast ratio being 4:1.

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References

1. Held G A, Dierking I, Kosbar L L, et al. Network morphology and switching transitions in polymer stabilized Cholesteric textures. Molecular Crystals and Liquid Crystals, 1999, 329(1): 473–481
2. Guillard H, Sixou P, Reboul L, et al. Electrooptical characterizations of polymer stabilized cholesteric liquid crystals. Polymer, 2001, 42(24): 9753–9762
3. Kang K, Chien L C, Sprunt S. Polymer-stabilized cholesteric liquid crystal microgratings: a comparison of polymer network formation and electro-optic properties for mesogenic and non-mesogenic monomers. Liquid Crystals, 2002, 29(1): 9–18
4. Priestley E B, Wojtowics P J, Sheng P. Introduction to Liquid Crystal. London: Plenum Press. 1974, 203–216
5. Moriya N, Uchida T, Matsushima K. Novel transmissive color filter using cholesteric liquid crystal with wide viewing angle. Journal of the Society for Information Display, 2003, 11(2): 409–412