Enhanced light absorption with a cholesteric liquid crystal layer

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Abstract: We discuss the trapping features of cholesteric liquid crystal as a self-organized photonic crystal and suggest it for absorption improvement. The imperfection of the absorbing surface is manifested by the reflection originating from the indispensable impedance mismatch. The reflection can be suppressed by an additional surface coating to reflect the light back to the absorber once again. In the simple consideration this reflection loop is possible only twice. For a right-handed CLC coating, the boundary reflection switches the light polarization from left to right circular in the first loop and it switches in the second loop back to the left circular polarization before the emerging light finally escapes from the absorbing process. The enhancement of light absorption is possible in the frequency range as large as the photonic bang gap of the cholesteric layer, which can be adjusted as desired.

OCIS codes: (160.1585) Chiral media; (160.3710) Liquid crystals; (230.5298) Photonic crystals; (230.3720) Liquid-crystal devices.

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#185332 - $15.00 USD Received 15 Feb 2013; revised 23 Mar 2013; accepted 24 Mar 2013; published 26 Mar 2013

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1. Introduction

Cholesteric liquid crystal (CLC) with its Bragg reflection is now considered as one-dimensional self-organizing photonic crystal (PC) [1] because CLC forms a fine helical structure and its optical properties are characterized by the tensor of dielectric permittivity rotating in space with the pitch in a scale of optical wavelength. The most important feature of PCs is the photonic band gap (PBG) in which the existence of light is forbidden within a certain range of optical wavelengths. The PCs [2] and other metamaterial technologies [3] permit close manipulation of light in a wide range of applications. One of the goals is the absorption of light over broad bandwidths necessary for solar batteries, thermal light emitting sources, bolometers and cross-talk reduction in optoelectronics.

Recently an idea was presented [4] to enhance absorption by an optical diode based on CLC layers [5] used as an optical coating [6]. This elegant idea has the advantage of easy tuning as the pitch of a CLC's helix can be adjusted [7–10]. This tunability is a required-but-difficult challenge in absorption using transformation optics [3] or plasmonic metallodielectric and metallosemiconductor structures [11].

This work aims to show that the devise proposed in [4] can be considerably simplified. More precisely, the only one layer of CLC can replace the optical diode consisting of two CLC layers and a half-wave plate.

2. The critical index match of the absorbing layer

At first, let's consider a homogeneous plain absorbing layer connected to a rear mirror with normal light incidence as shown in Fig. 1(a). The formalism of transfer matrix [13] is appropriate for this problem. We put the boundary condition for the light at the mirror surface as

$$\begin{bmatrix} A \\ B \end{bmatrix}_{\text{mirror}} = \begin{bmatrix} 1 \\ -1 \end{bmatrix}, \tag{1}$$

where A and B are the electric field amplitudes of the forward and backward Rayleigh waves of the light described by

$$E = Ae^{-i\omega t+ikz} + Be^{-i\omega t-ikz}, \tag{2}$$

where ω is the angular frequency, t is the time, z is the coordination along the layer normal direction, and k (= $2\pi/\lambda$) is the angular wavenumber.

The propagation matrix for the layer has the form

$$\mathbf{P} = \begin{bmatrix} e^{-i\phi} & 0 \\ 0 & e^{i\phi} \end{bmatrix}, \tag{3}$$

where the phase incursion $\phi = 2\pi nL/\lambda$, with L representing the layer thickness, λ the vacuum wavelength, and n (= Re(n) + iIm(n)) the refractive index of the absorbing layer. Note that the

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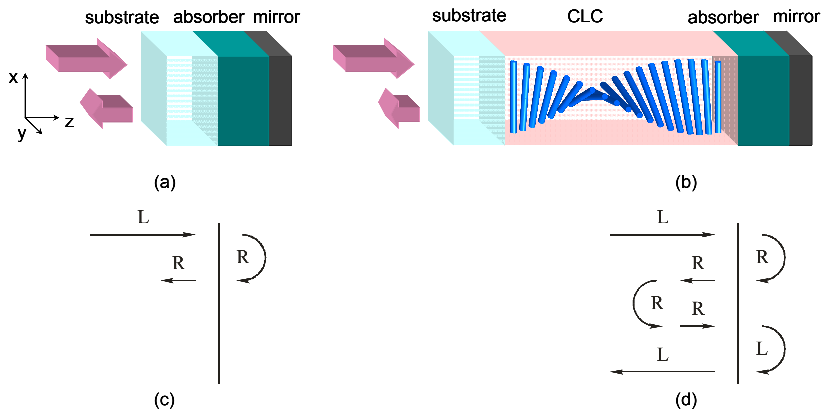

Fig. 1. (a) Light absorbing layer with a mirror at the back surface. (b) Enhanced light absorption with a CLC layer. (c) and (d) Schematics showing the paths of light and changes of the polarization states in cases (a) and (b), respectively [12]. L: left circularly polarized light; R: right circularly polarized light. The substrate is semi-infinite.

refractive index can be expressed as $n = \varepsilon^{1/2}$ for nonmagnetic media. The phase sign assumption in the form $E = Ae^{-i\omega t+ikz}$ leads to Im(n) > 0 for the absorber. The dynamic matrix (see Eq. (16) in [14] and Eq. (7) in [13]) for the front layer surface has the form

$$\mathbf{D} = \mathbf{D}_1^{-1}\mathbf{D}_2 = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}^{-1} \begin{bmatrix} 1 & 1 \\ \tilde{n} & -\tilde{n} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} + \frac{\tilde{n}}{2}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}, \tag{4}$$

where $\tilde{n} = n / n_0$, with n_0 denoting the refraction index of the external medium. The external radiation is expressed as

$$\begin{bmatrix} A_0 \\ B_0 \end{bmatrix} = \begin{bmatrix} A_0 \\ rA_0 \end{bmatrix} = \mathbf{DP}\begin{bmatrix} A \\ B \end{bmatrix}_{\text{mirror}}, \tag{5}$$

where r is the amplitude reflection coefficient. Substitution of Eqs. (1), (3) and (4) into Eq. (5) gives:

$$r = -\frac{\tilde{n}\cos(\phi) + i\sin(\phi)}{\tilde{n}\cos(\phi) - i\sin(\phi)}. \tag{6}$$

It is necessary to minimize the reflectance $R = |r|^2$ in order to achieve maximal absorption (1 – R). Equating reflection to zero gives zero numerator in Eq. (6):

$$\tilde{n} = -i\tan(\phi_0\tilde{n}), \tag{7}$$

where $\phi_0 = 2\pi n_0 L / \lambda$ is presumably a real number. The resembling transcendental equations occur in the heat-flow problem with derivative boundary conditions [15] and in quantum mechanics one-dimensional square-well potential problem [16]. These equations have no general analytical solution and have to be solved numerically or graphically. Equation (7) has an infinite series of solutions (reflection zeros) for $\tilde{n}$ at the fixed ratio L/λ. According to the coupled-mode theory [17] the reflection zero occurs every time when the unloaded quality factor in the absorbing layer is equal to the external quality factor. This condition of critical match leads to destructive interference of all reflections. The power entering the cavity (the absorbing layer in our case) is maximized for a given incident power while the reflected power is minimized.

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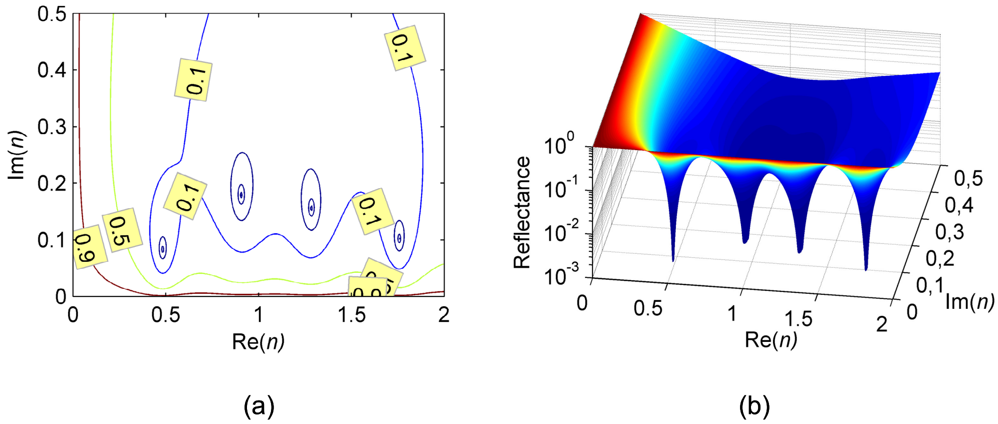

Fig. 2. Reflectance versus the refractive index n of an absorbing layer with a mirror back surface at $L/\lambda = 1$ and $n_0 = 1$. (a) The contour plot and (b) the reflectance as a function of the complex index showing four reflection zeros at $n = 0.48 + 0.08i$, $0.90 + 0.17i$, $1.29 + 0.15i$, $1.76 + 0.10i$.

It is impossible to find general analytical solution of the transcendental equation, Eq. (7). Numerical illustration of the first four reflection zeros is presented in Fig. 2. This simple absorbing model has an intrinsic disadvantage. The critical matching layer demands a fixed light frequency and ceases to totally absorb the wideband radiation. Of course this is not the case in the limit of infinite absorber with low impedance mismatch: $\tilde{n} \to 1, L\,\mathrm{Im}(\tilde{n}) \to \infty$. Nevertheless, there are many applications where the size of absorber is critically important.

3. Absorption enhancement by a CLC layer

Now we introduce an enhancement for the absorber by adding a CLC layer (Fig. 1(b)). The light polarization is traced by the arrow sequence. The idea is based on the facts that reflection at the boundary of isotropic media changes the polarization sign and that CLC reflection conserves the polarization sign [18]. The total reflection of a right circularly polarized wave occurs inside the PBG in the thick-enough right-handed CLC layer. The absorption process is repeated twice. In the first loop of absorption R part of energy is reflected into the CLC. And in the second loop only R part of R is reflected. In this case we have squared reflection given by the following doubled-reflection logarithm:

$$\log R_{\mathrm{PBG}} = 2\log R. \tag{8}$$

Numerical evaluation using Berreman's method [14,19,20] proves that this estimation is valid. This is demonstrated in Fig. 3 for some typical parameters: The light normally enters the index $n = 1.6\ (1 + 0.3i)$ and thickness $L = 1\ \mu$m. The CLC layer possesses ordinary and extraordinary refractive indices $n_o = 1.5$ and $n_e = 1.7$, length $L_{\mathrm{CLC}} = 3\ \mu$m, and helix pitch $P = 0.3125\ \mu$m.

In Eq. (8) the assumption was made that at the boundary of the isotropic absorber and the anisotropic CLC layer the polarization sign changes from left to right (see Fig. 1(b)). It is approximately valid under the condition

$$\frac{(n_e - n_o)}{|n - n_0|} < 2. \tag{9}$$

In the example this ratio is 0.42. The reflected light is right-polarized, but not exactly circular. This ellipticity leads to less efficient CLC reflection, but, surprisingly, more than two loops of absorption. Besides, an additional boundary between the isotropic substrate and anisotropic CLC produces reflection interference, causing its deviation from the estimation of Eq. (8).

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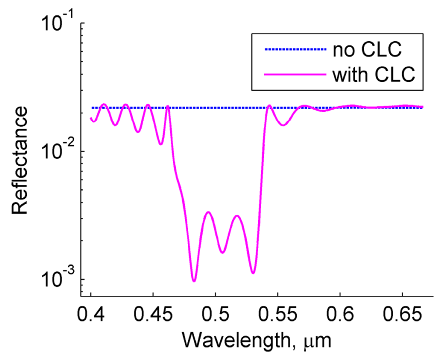

Fig. 3. Calculated reflection spectra in logarithmic scale for the models of Fig. 1(a) (blue dotted curve) and Fig. 1(b) (magenta solid curve) near the PBG of a CLC. The parameters are described in the text. The interference oscillations are due to the additional boundary.

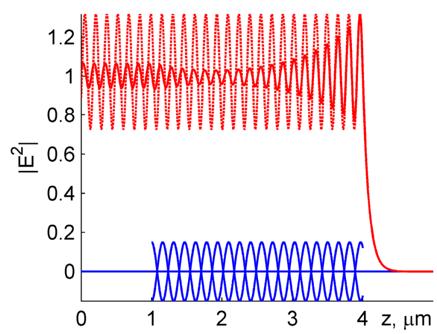

Fig. 4. Calculated $|E|^2(z)$ profiles (maximum of oscillating electric strength square) inside the absorber structure without a neighboring CLC (dotted curve) and with a CLC layer (solid curve) schematically given by Figs. 1(a) and 1(b), respectively. It is normalized to an incident vacuum value of $|E_0|^2 = 1$. The CLC layer in Fig. 1(b) is situated between z = 1 and 4 μm as shown by schematics (blue sinusoidal lines show the CLC director rotation). The parameters are the same as used to produce Fig. 3. The optical wavelength is at the CLC PBG center: $\lambda = P(n_o + n_e)/2 = 0.5$ μm.

Figure 4 shows the localization of field near the absorber boundary, which also proves that the schematics in Figs. 1(c) and 1(d) are valid. Oscillations of the $|E|^2(z)$ profile are produced by the reflected wave. Large oscillations in the dashed curve manifest higher reflection $R = 2.2 \cdot 10^{-2}$. The solid curve shows that the same oscillations near the absorbing layer boundary are substantially damped by the CLC layer, yielding low reflectance of $R_{PBG} = 2.4 \cdot 10^{-3}$. The CLC double enhancement deteriorates because of the additional reflection at the boundary between the substrate and CLC. This additional reflection is $R \sim 2.0 \cdot 10^{-3}$. In our model it cannot be lowered less than it is at half the CLC anisotropy: $|n_e - n_o|/2 \le \max\left(|n_e - n_0|, |n_o - n_0|\right)$.

The field distribution forms a surface state at the boundary between CLC and absorber. This surface state localization is no more than twice the incoming field. So it should not be confused with optical Tamm states [21].

Figure 5 shows reflection comparison for arbitrary wavelengths and loss tangent: $\tan\delta = \mathrm{Im}(\tilde{n})/\mathrm{Re}(\tilde{n})$, $\tilde{n} = |\tilde{n}|\exp(i\delta) = 1.6(1 + i\tan\delta)$. When $\tan\delta$ = 0.06 the absorber is close to the critical match condition and the dotted reflectance curve shows three gaps.

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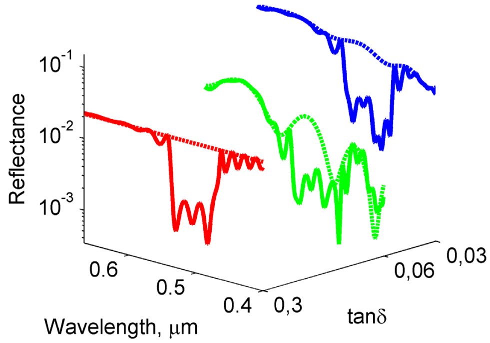

Fig. 5. Calculated reflectance without CLC (dotted curves) and with a CLC layer (solid curves) for tan $\delta = 0.03$ (blue), 0.06 (green), 0.3 (red). Parameters are the same as used to produce Fig. 3. The middle plot (green) has a condition close to the critical match with reflection zero.

The most shortwave gap at $\lambda = 0.41$ μm gives $R = 6{\cdot}10^{-4}$. The bandwidth of these gaps is several times narrower than the bandwidth of the CLC PBG. Far from this critical match condition the estimation of Eq. (8) is more reliable. The reflection is higher when tan δ exceeds a critical one or when it is less than a critical one. The former corresponds to a metallic mirror with the skin effect and the latter is for a weak absorber. The weak absorber breaks the circularity condition of Eq. (9). Nevertheless, estimation of Eq. (8) is appropriate. It is explained by the low reflection from the border between a weak absorber and the CLC layer which can be neglected compared with the mirror reflection.

4. Concluding remarks

The double enhancement of optical absorption using a CLC layer within the PBG region was demonstrated for the light with polarization helicity opposite to CLC helicity. In [9] the absorption enhancement is proposed to be achieved independent of the polarization of the incident light, using a splitting device. The absorption mechanism is proven to be based on the switching of circular polarization in boundary reflection. This qualitative reasoning is estimated by logarithmic doubling of reflectance suppression (given by Eq. (8)). The estimation works both for high and low absorption materials. For intermediate absorption materials the critical match condition (Eq. (7)) is found rigorously. This critical match provides narrow wavelength region of perfect absorption without CLC layer. In this case the interferential nature of reflection zeros deteriorates double enhancement due to the additional reflections at the boundaries. Hence this additional reflection could be reduced, for example, by homeotropic boundary conditions for the CLC layer. Such an apodization improvement needs compensation in a thicker CLC layer to provide the same depth of the PBG.

A simple and important question arises: Why not make the double enhancement to be doubled again by an additional CLC layer, or make a total light trap by a large series of CLC layers? The answer is negative and is hidden in dimensionality of polarization. The light wave has only two orthogonal polarizations. The RCP twice absorption is achieved at the expense of the LCP total reflection from the CLC layer. This polarizational degree of freedom is used to increase the absorption pathway. The analogous but much more elegant approach is known in the numerical calculations methods, namely in the problem of the truncation of finite-difference time-domain lattices. Such problem is solved by introducing a perfectly matched layer of an absorbing artificial substance composed of a uniaxial anisotropic material [22].

Acknowledgments

This work was financially supported by the National Science Council, Taiwan, under Grant No. NSC 101-2112-M-009-018-MY3 and by the Siberian Branch of the Russian Academy of Sciences (SB RAS) through Grants Nos. 43, 101 and 24.29, 24.32 and by the Ministry of Education and Science of the Russian Federation (state contract no. 14.V37.21.0730).

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