# Tunable all-optical switching in periodic structures with liquid-crystal defects

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**Abstract:** We suggest that tunable orientational nonlinearity of nematic liquid crystals can be employed for all-optical switching in periodic photonic structures with liquid-crystal defects. We consider a one-dimensional periodic structure of Si layers with a local defect created by infiltrating a liquid crystal into a pore, and demonstrate, by solving numerically a system of coupled nonlinear equations for the nematic director and the propagating electric field, that the light-induced Freedericksz transition can lead to a sharp switching and diode operation in the photonic devices.



**OCIS codes:** (190.4420) Nonlinear optics, transverse effects in; (190.5940) Self-action effects

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## 1. Introduction

During the past decade, photonic crystals (artificially fabricated one-, two- and three-dimensional periodic dielectric materials) have attracted a great deal of interest due to their ability to inhibit the propagation of light over special regions known as photonic band gaps [1]. Such photonic bandgap materials are expected to revolutionize integrated optics and micro-photonics due to an efficient control of the electromagnetic radiation they provide, in such a way as semiconductors control the behavior of the electrons [2].

In general, the transmission of light through photonic crystals depends on the geometry and the index of refraction of the dielectric material. Tunability of the photonic bandgap structures is a key feature required for the dynamical control of light transmission and various realistic applications of the photonic crystal devices. One of the most attractive and practical schemes for tuning the band gap in photonic crystals was proposed by Busch and John [3], who suggested that coating the surface of an inverse opal structure with a liquid crystal could be used to continuously tune the band gap, as was confirmed later in experiment [4]. This original concept generated a stream of interesting suggestions for tunable photonic devices based on the use of liquid crystals infiltrated into the pores of a bandgap structure [5]. The main idea behind all those studies is the ability to continuously tune the bandgap spectrum of a periodic dielectric structure using the temperature dependent refractive index of a liquid crystal [4, 5, 6, 7], or its property to change the refractive index under the action of an applied electric field [8, 9, 10].

Another idea of the use of liquid crystals for tunability of photonic crystals is based on infiltration of individual pores [11] and creation of liquid crystal defects [12, 13, 14], and even defect-induced waveguide circuits [11]. In this case, the transmission properties can be controlled, for example, by tuning resonant reflections associated with the Fano resonances [15, 16] observed when the frequency of the incoming wave coincides with the frequency of the defect mode. As a result, the defect mode becomes highly excited at the frequency of the resonant reflection, and it can be tuned externally, again by an electric field or temperature.

However, liquid crystals by themselves demonstrate a rich variety of nonlinear phenomena (see, for example, Refs. [17, 18, 19, 20]). Therefore, nonlinear response of liquid crystals can

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be employed for all-optical control of light propagation in periodic structures and tunability of photonic crystals. In this paper, for the first time to our knowledge, we analyze the possibility of *tunable all-optical switching* in one-dimensional periodic structure with a liquid crystal defect. We demonstrate that the light field with the intensity above a certain critical value corresponding to the optical Freedericksz transition changes the optical properties of the liquid-crystal defect such that the nonlinear transmission of the photonic structure allows for all-optical switching, and the similar concept can be employed for creating of a tunable all-optical diode.

## 2. Nonlinear transmission of a liquid crystal slab

First, we study the light transmission of a single slab of nematic liquid crystal and derive a system of coupled nonlinear Eqs for the liquid-crystal director reorientation in the presence of the propagating electric field of a finite amplitude. The corresponding steady-state Eq. for the director $\mathbf{n}$ can be obtained by minimizing the free energy which can be written in the following form [17, 21]

$$\begin{aligned} f &= f_{\mathrm{el}} + f_{\mathrm{opt}}, \\ f_{\mathrm{el}} &= \frac{1}{2}\left[K_{11}(\nabla\cdot\mathbf{n})^2 + K_{22}(\mathbf{n}\cdot\nabla\times\mathbf{n})^2 + K_{33}(\mathbf{n}\times\nabla\times\mathbf{n})^2\right], \\ f_{\mathrm{opt}} &= -(1/16\pi)\mathbf{D}\cdot\mathbf{E}^*, \end{aligned} \tag{1}$$

where $f_{\mathrm{el}}$ is the elastic part and $f_{\mathrm{opt}}$ is the optical part of the energy density. Here $K_{11}$, $K_{22}$ and $K_{33}$ are splay, twist, and bend elastic constants, respectively, $\mathbf{D} = \hat{\varepsilon}\mathbf{E}$, $\hat{\varepsilon}$ is the dielectric tensor, and the real electric field is taken in the form $\mathbf{E}_{real} = (1/2)[\mathbf{E}(\mathbf{r})\exp(-i\omega t) + \mathbf{E}^*(\mathbf{r})\exp(i\omega t)]$.

We assume that linearly polarized light wave propagates normally to the liquid-crystal slab with the initial homeotropic director orientation along $z$ [see Fig. 1(a)]. Under the action of the electric field polarized outside the slab along $x$, the director can change its direction in the $(x,z)$ plane and, therefore, we write the vector components of the director in the form $\mathbf{n} = \{\sin\phi(z), 0, \cos\phi(z)\}$. Then the elastic part of the free energy density can be written as

$$f_{\mathrm{el}} = \frac{1}{2}\left(K_{11}\sin^2\phi + K_{33}\cos^2\phi\right)\left(\frac{d\phi}{dz}\right)^2 . \tag{2}$$

Taking into account that the dielectric tensor $\hat{\varepsilon}$ can be expressed in terms of the director components, $\varepsilon_{ij} = \varepsilon_{\perp}\delta_{ij} + \varepsilon_a n_i n_j$, where $\varepsilon_a = \varepsilon_{||} - \varepsilon_{\perp}$ and $\varepsilon_{||}$, $\varepsilon_{\perp}$ are the liquid crystal dielectric constants at the director parallel and perpendicular to the electric vector, we can write

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_{\perp} + \varepsilon_a\sin^2\phi & 0 & \varepsilon_a\sin\phi\cos\phi \\ 0 & \varepsilon_{\perp} & 0 \\ \varepsilon_a\sin\phi\cos\phi & 0 & \varepsilon_{\perp} + \varepsilon_a\cos^2\phi \end{pmatrix} . \tag{3}$$

As a result, the optical part of the free energy density takes the form

$$f_{\mathrm{opt}} = -\frac{\varepsilon_a}{16\pi}\left[\sin^2\phi|E_x|^2 + \cos^2\phi|E_z| + +\sin\phi\cos\phi(E_xE_z^* + E_zE_x^*)\right] - \frac{\varepsilon_{\perp}}{16\pi}|\mathbf{E}|^2 .$$

After minimizing the free energy (1) with respect to the director angle $\phi$, we obtain the nonlinear equation for the director in the presence of the light field

$$A(\phi)\frac{d^2\phi}{dz^2} - B(\phi)\left(\frac{d\phi}{dz}\right)^2 + \frac{\varepsilon_a\varepsilon_{\perp}(\varepsilon_a+\varepsilon_{\perp})|E_x|^2\sin 2\phi}{16\pi(\varepsilon_{\perp}+\varepsilon_a\cos^2\phi)^2} = 0, \tag{4}$$


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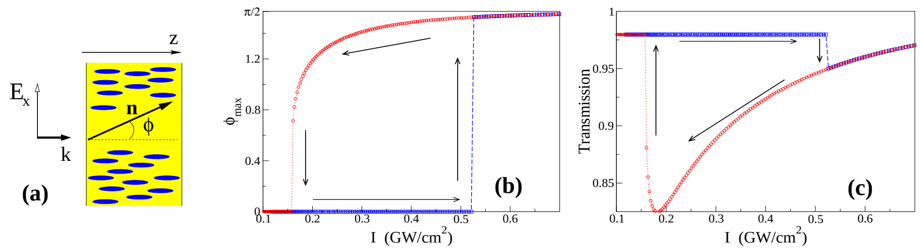


Fig. 1. Nonlinear transmission of a liquid-crystal slab. (a) Schematic of the problem. (b,c) Maximum angle of the director and transmission vs. the light intensity in the slab. Blue and red curves correspond to the increasing and decreasing light intensity, respectively.

where $A(\phi) = (K_{11}\sin^2\phi + K_{33}\cos^2\phi)$, $B(\phi) = (K_{33} - K_{11})\sin\phi\cos\phi$, and we take into account that, as follows from $D_z = 0$, that the electric vector of the light field has the longitudinal component, $E_z = -(\varepsilon_{xz}/\varepsilon_{zz})E_x = -[\varepsilon_a \sin\phi\cos\phi/(\varepsilon_\perp + \varepsilon_a\cos^2\phi)]E_x$ (see also Ref. [17]).

From the Maxwell's equations, we obtain the equation for the electric field $E_x$,

$$\frac{d^2E_x}{dz^2} + k^2\frac{\varepsilon_\perp(\varepsilon_\perp + \varepsilon_a)}{\varepsilon_\perp + \varepsilon_a\cos^2\phi}E_x = 0, \tag{5}$$

where $k = 2\pi/\lambda$. Moreover, it can be shown [17, 19] that the $z$ component of the Poynting vector $I = S_z = (c/8\pi)E_xH_y^*$ remains constant during the light scattering and, therefore, it can be used to characterize the nonlinear transmission results.

As the boundary conditions for the coupled nonlinear Eqs (4) and (5), we assume that there is an infinitely rigid director anchoring at both surfaces of the slab, i.e.

$$\phi(0) = \phi(L) = 0, \tag{6}$$

and also introduce the scattering amplitudes for the optical field

$$E_x(z) = \begin{cases} \mathscr{E}_{\rm in}\exp(ikz) + \mathscr{E}_{\rm ref}\exp(-ikz), & z \le 0, \\ \mathscr{E}_{\rm out}\exp(ikz), & z \ge L, \end{cases} \tag{7}$$

where $L$ is the thickness of the liquid-crystal slab, $\mathscr{E}_{\rm in}$, $\mathscr{E}_{\rm ref}$, and $\mathscr{E}_{\rm out}$ are the electric field amplitudes of incident, reflected, and outgoing waves, respectively.

To solve this nonlinear problem, first we fix the amplitude of the outgoing wave $\mathscr{E}_{\rm out}$ and find unique values for the amplitudes of the incident, $\mathscr{E}_{\rm in}$, and reflected , $\mathscr{E}_{\rm ref}$, waves. By using the so-called *shooting method* [22], in Eq. (4) for the director we fix the amplitude of the outgoing wave and, assuming that $\phi(L) = 0$ at the right boundary, find the derivative $(d\phi/dz)_{z=L}$ such that after integrating we obtain a vanishing value of the director at the left boundary, i.e. $\phi(0) = 0$. Because Eq. (4) is a general type of the nonlinear pendulum equation, we look for periodic solutions with the period $2L$. Obviously, there exists an infinite number of such solutions and, therefore, there is an infinite set of the derivatives $(d\phi/dz)_{z=L}$ which satisfy Eq. (4) and the condition (6). All such solutions correspond to some extrema points of the free energy of the system. However, we are interested only in that solution which realizes the minimum of the free energy. By analyzing our coupled nonlinear equations in a two-dimensional phase space, we can show that the corresponding solution lies just below the separatrix curve, and it has no node between the points $z = 0$ and $z = L$. This observation allows us to reduce significantly the domain for our search for the required values of the derivative $(d\phi/dz)_{z=L}$.

The obtained solutions can be characterized by the maximum angle $\phi_{\rm max}$ of the director deviation which, as is intuitively clear, should be reached near or at the middle of the slab. In

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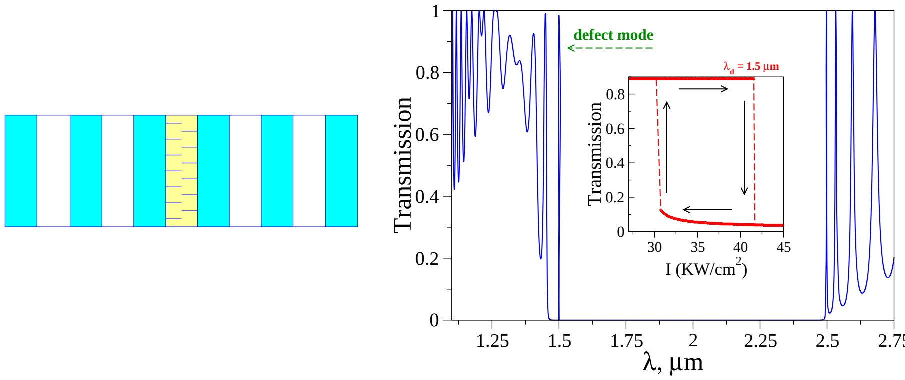


Fig. 2. Transmission of an one-dimensional periodic structure with an embedded liquid-crystal defect. In the linear regime, the transmission is characterized by the presence of an in-gap resonant peak due to the excitation of a defect mode. Nonlinear transmission displays bistability at the defect-mode frequency with two different thresholds for "up" and "down" directions and a hysteresis loop (see the insert).

Fig. 1(b,c), we plot the maximum angle $\phi_{\rm max}$ and the transmission coefficient of the liquid-crystal slab, defined as $T = |\mathscr{E}_{\rm out}|^2/|\mathscr{E}_{\rm in}|^2$, vs. the light intensity. For numerical calculations, we use the parameters $K_{11} = 4.5 \times 10^{-7}$ dyn, $K_{33} = 9.5 \times 10^{-7}$ dyn, $\varepsilon_a = 0.896$, $\varepsilon_\perp = 2.45$, $L = 200nm$, and $\lambda = 1.5\mu m$, that correspond to the PAA liquid crystal [23]; because of a lack of the corresponding data at the wavelength $\lambda = 1.5\mu m$, the values of the dielectric constant are taken from the optical range.

From the results presented in Fig. 1(b,c), we observe sharp jumps of the director maximum angle $\phi_{\rm max}$ and the transmission coefficient $T$ due to the *optical Freedericksz transition* in the liquid-crystal slab. However, a variation of the transmission coefficient during this process is not larger than 15%. The threshold of the optical Freedericksz transition appears to be different for the increasing and decreasing intensity of the incoming light, so that this nonlinear system is bistable, and it displays a hysteresis behavior. The bistable transmission of the liquid-crystal slab is similar to that predicted for the slab of PAA liquid crystal in the geometric optics approximation [19], and such a behavior is explained by the existence of the metastable state which the system occupies at the decreasing light intensity [17, 19].

## 3. Liquid-crystal defect in a periodic photonic structure

Now, we study the similar problem for a liquid-crystal defect infiltrated into a pore of the periodic structure created by Si layers with the refractive index $n = 3.4$. For simplicity, we consider a one-dimensional structure with the period $a = 400nm$ and the layer thickness $d_1 = 200nm$, that possesses a frequency gap between $1.4\mu m$ and $2.5\mu m$. We assume that one of the holes is infiltrated with a PAA nematic liquid crystal with $\varepsilon_\perp = 2.45$. Such a defect modifies the linear transmission of the periodic structure by creating a sharp defect-mode peak at the wavelength $\lambda_d \approx 1.5\mu m$, as shown in Fig. 2.

To solve the nonlinear transmission problem, we employ the transfer matrix approach [24] implementing it for the solution of the full system of coupled Eqs (4) and (5). By tuning the input intensity at the defect mode, we observe the same scenario as for a single liquid-crystal slab [cf. the insert in Fig. 2 and Fig. 1(c)]. Namely, there exists a hysteresis loop in the transmission with two different thresholds for the increasing and decreasing intensities. The difference is, however, in the values. Due to a small width of the defect-mode resonance, a finite reorienta-

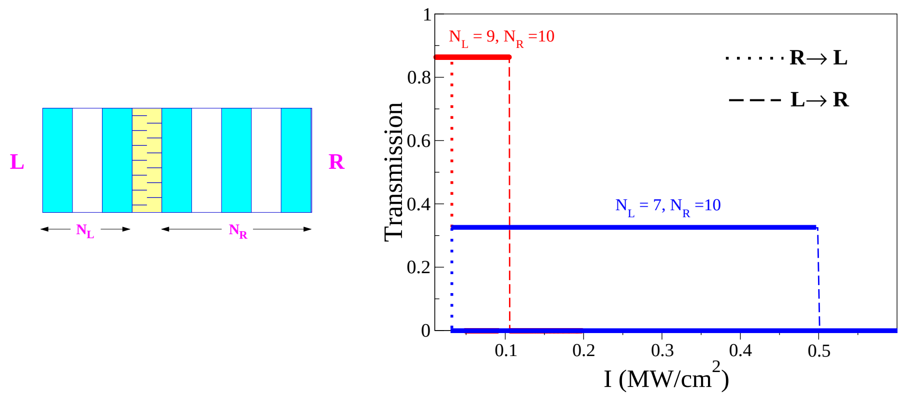


Fig. 3. Example of a tunable all-optical diode based on the optical Freedericksz transition in a liquid-crystal defect. Asymmetrically placed defect leads to different threshold intensities of the switching for the waves propagating from the right and left, respectively.

tion of the director leads to a sharp (up to 90%) change in the transmission. Another significant difference is that the threshold values are *lower by four orders of the magnitude*, for a given periodic structure for which we take 10 layers from each side of the defect.

Finally, we notice that in a finite periodic structure the defect placed asymmetrically (see Fig. 3) allows to create a nonreciprocal device when the threshold intensities for the molecular reorientation differ for the light propagating from the right and left. This feature is associated with the operation of an *optical diode* [25, 26]. As can be seen in Fig. 3, by shifting the infiltrated liquid-crystal defect closer to one of the edges of the structure and fixing the total length of the structure, we can increase the switching power and extend the diode operation region decreasing the transmission power. Moreover, these results show that the threshold intensities depend strongly on the number of periods to the structure edge, due to a stronger confinement of the defect mode. Also, this gives us a possibility to reduce significantly the switching power simply by taken larger number of periods in the photonic structure.

## 4. Conclusions

We have demonstrated that the orientational nonlinearity of nematic liquid crystals can be employed to achieve tunable all-optical switching and diode operation in periodic photonic structures with infiltrated liquid-crystal defects. For the first time to our knowledge, we have solved a coupled system of nonlinear equations for the nematic director and the propagating electric field for the model of a one-dimensional periodic structure created by Si layers with a single (symmetric or asymmetric) pore infiltrated by a liquid crystal. We have demonstrated that the threshold of the optical Freedericksz transition in the liquid-crystal defect is reduced dramatically due to multiple reflections in the periodic structure, so that such a defect may allow a tunable switching and diode operation in the photonic structure.

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