Optical switches based on partial band gap and anomalous refraction in photonic crystals modulated by liquid crystals

Yao-Yu Wang[a], Jiun-Yeu Chen[b], and Lien-Wen Chen[a,*]

[a]*Department of Mechanical Engineering, National Cheng Kung University, Tainan 701, Taiwan*
[b]*Department of Electronic Commerce, Hsing Kuo University of Management, Tainan 709, Taiwan*
[*]*Corresponding author: chenlw@mail.ncku.edu.tw*

Abstract: Optical switches using two transmission properties in triangular photonic crystals infiltrated with liquid crystals (LCs) are investigated for incorporation in wave-guided structures for planar lightwave circuits. The two devices employ partial band gap and anomalous refraction, which are based on the anisotropic characteristics of LC reorientation under applied fields. These switches have been designed and their parameters have been analyzed by the plane wave and finite-difference time-domain calculations. In the on/off switching system, the partial band gap can be controlled when the normalized operation frequency is 0.27. The anomalous refraction can be modulated to deflect a light beam with a maximum deflection angle ~57° when the frequency is 0.3. The tunability induced by LCs can create a sharp switching in the photonic devices.

OCIS codes: (130.1750) Component; (230.3720) Liquid-crystal devices; (999.9999) Photonic crystals.

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1. Introduction

All-optical switching configurations in integrated optical circuits will be a valuable component to switch the traffic directly in the optical networks. These devices can function without the need of several optical-electrical conversions. For many interesting signal processing applications and all-optical devices, photonic crystals (PhCs) and nonlinear optics are two areas of current consideration. PhCs that have an ordered structure with a modulation of refractive index or dielectric constant have attracted considerable attention from both fundamental and practical points of views. The periodic structures that can create photonic band-gaps (PBGs) are designed to modify the features of light propagating within them. PhC-based devices have provided opportunities for achieving photonic integrated systems with many important applications including display technology, telecommunication and fiber optics [1]. If nonlinearity introduced into a PhC can be excited, the response of the PBG material can be varied dramatically by a light signal to modify the index of refraction. Optical bistability existing in nonlinear systems has been successfully used in optical switches [2, 3]. However, it is important to understand how the dynamic features of light interacting with PBG structures can develop promptly, and how nonlinearities doped into the PBG material can be employed to design useful devices.

Recently, many studies about anomalous refraction effects in PhCs have triggered intensive work on the design of optical systems [4]. The effects can act in optical frequency region with potential advantages over conventional components. In the past, the enormous majority of research in the PBG system has been devoted to applications of the forbidden band and the defects introduced in the PhCs [1]. Besides, the PhCs can allow phase matching to the radiation modes (that lie above the air light line) at the Brillouin zone boundaries and can be used to enhance extraction of light in the vertical direction from semiconductor light-emitting diodes [5]. Later, the feature of an effective negative refractive index in the vicinity of PBG edges was investigated theoretically by Notomi [6]. The research has been extended to new transmission properties, such as the superlens [7], superprism [8], self-guiding [9], and open resonators [10].

Liquid crystal (LC) materials have been drawing much attention to optical communication for their unique abilities to give optical performance comparable to optomechanical devices. Using LCs to obtain some degree of tunability of the PhCs through electro-optic effects was first introduced by John and Busch [11]. The optical anisotropy of LCs due to the molecule alignment and texture allows one to easily modify the optical properties of PhCs with them. LCs are interesting materials to make optical switches. Main benefits are their transparency in the near infrared spectrum, high birefringence, and refractive index distributed between 1.4 and 1.7 (that is close to glass, silica, and polymers) [12]. In two-dimensional (2D) PhCs using LCs, the tunabilities of photonic band structures can be realized through electro-optic effects [13].

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Integrated optical circuits can be categorized into two main classes: free-space and wave-guided structures. Through PhCs, the optical switches belonging to the latter class can be based on the controllable partial PBG or on diffraction behavior obtained from spatial variations. A PhC device fabricated from electro-optic materials can achieve the modification of the band structure to change the light propagation direction [14, 15]. The mechanical stress resulting in the changes in the periodicity of the PhC can provide a wide tunability in the beam direction [16]. Negative refraction in the PhCs incorporating the superconductor constituents could be tuned by temperatures, which could make the scanning angle of refractions [17]. These designs in light of the dispersion properties of PhCs are the promising application of beam coupling to planar structures. The component proposed in this article is capable of realizing electro-optical switching. We consider a triangular-lattice PhC consisting of LC pillars embedded in a thick slab of dielectric matrix. Two types of optical switches based on the anisotropic properties of a 2D PhC are investigated for the light with two kinds of frequencies: the frequencies at the partial band gap and at the second band of the band structure for the transversal electric (TE) mode. The configuration of the switch via the concept of constant-frequency contours (CFCs) is simple and compact. To obtain photonic band diagrams and CFCs, the plane wave expansion method was used. The finite-difference time-domain (FDTD) calculation was applied to analyze electromagnetic wave propagation in the optical switches. The design, performance and operation of the switches are discussed in this paper.

2. Numerical procedures

The partial band gap and the anomalous refraction phenomenon at frequencies corresponding to the stop band and the specific photonic band of a 2D PhC are investigated by means of a CFC analysis and FDTD simulations. Obtaining the resultant photonic dispersion requires Bloch modes in the periodic structures. The simplified Maxwell's equation for the magnetic filed $\mathbf{H}(\mathbf{r})$ can be expressed as:

$$\nabla\times[\frac{1}{\varepsilon(\mathbf{r})}\nabla\times\mathbf{H}(\mathbf{r})]=(\frac{\omega}{c})^2\mathbf{H}(\mathbf{r}) . \tag{1}$$

The dielectric constant $\varepsilon(\mathbf{r})$ of a PhC structure is periodic with respect to the lattice vector and can be expanded in a Fourier series on the reciprocal lattice vector $\mathbf{G}$:

$$\varepsilon_{i,j}(\mathbf{r})=\sum_{\mathbf{G}}\varepsilon_{i,j}(\mathbf{G})e^{j\mathbf{G}\bullet\mathbf{r}} \quad (i,\, j=x,\, y) . \tag{2}$$

In general optics, the uniaxial material has two different principal refractive indices. For nematic LCs, the ordinary-refractive index n_o and extraordinary-refractive index n_e are for light with electric field polarization perpendicular and parallel to the director, respectively. When the nematic director rotates in the *xy* plane, the components of the dielectric tensor can be represented as [13]:

$$\varepsilon_{x,x}(\mathbf{r})=n_o^2(\mathbf{r})\sin^2\Phi+n_e^2(\mathbf{r})\cos^2\Phi , \tag{3}$$

$$\varepsilon_{y,y}(\mathbf{r})=n_o^2(\mathbf{r})\cos^2\Phi+n_e^2(\mathbf{r})\sin^2\Phi , \tag{4}$$

$$\varepsilon_{x,y}(\mathbf{r})=\varepsilon_{y,x}(\mathbf{r})=[n_e^2(\mathbf{r})-n_o^2(\mathbf{r})]\sin\Phi\cos\Phi , \tag{5}$$

where Φ is the rotation angle of the director. The director is presented by $\mathbf{n}$=(cosΦ, sinΦ). Plane wave expansion method was employed to calculate photonic band diagram and CFCs [18]. We examine mainly TE modes (electric fields lie parallel to the *xy* plane). Because of the directors parallel to the 2D plane, the electric fields with the TE mode can be strongly influenced by rotating the directors of LCs. Besides, the numerical problem in obtaining the

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eigenvalues from the Fourier coefficients of the inverse dielectric tensors can be solved by the method proposed by Ho *et al*. [19]. The Bloch waves to compute the eigenvalues are expanded by 441 plane waves. The FDTD method with uniaxial perfectly matched layer boundary conditions [20] was used to simulate the transmission properties for the tunabilies of the partial band gap and the anomalous refraction effect. The changes in the rotation angle of the director can produce large changes in the transmission spectrum or in the direction of the outgoing light. The results of a CFC analysis can serve as a theoretical prediction to be compared with the FDTD data.

3. Photonic crystals infiltrated with liquid crystals

The device concept is a triangular PhC of LC pillars in a dielectric substrate, as shown in Fig. 1. The nematic director is parallel to the 2D plane. It is assumed that the produced PhC holes infiltrated with LCs are untreated in the surface. Hence, the average index of the LC regions can be obtained without the strong anchoring effect of LCs. The optical anisotropy of LCs can be easily controlled through the variation of an in-plane electric field. The CFCs of the structure also change with the variation, and the refractive properties for a given value of the Bloch wave vector **k** can be modulated. A critical voltage is required to be small for the practical application of LCs in the tunable PhC. The LC 5CB is used since it has small critical voltage value and large optical anisotropy [12]. The value of refractive indices of LC 5CB is taken as n_o=1.522 and n_e=1.706 on the assumption that PhC operates at room temperature. When the external electric field is not applied, the LC becomes isotropic and its average refractive index is $n_{av}=(2n_o+n_e)/3=1.583$. However, the optical anisotropy of the structure is not significant since the refractive index of Si (n=3.45) compared with that of LC is higher. In order to obtain a higher anisotropy, a larger radius r=0.35a is adopted to improve the anisotropy.

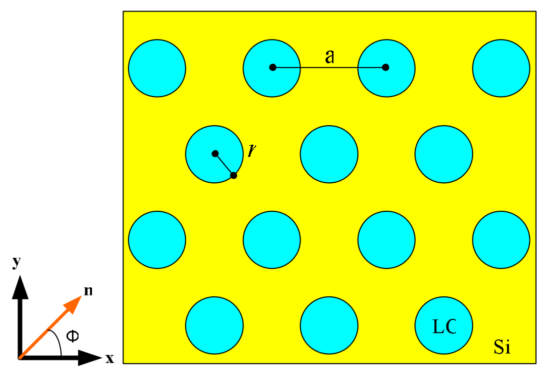

Fig. 1 Sketch of the triangular-lattice PhC structure composed of pillars filled with the nematic LCs. The LC director **n** at a rotation angle Φ is parallel to the *xy* plane when an in-plane electric field is applied.

4. Tunable features and optical switches

The band structure of the PhC for the TE polarization is shown in Fig. 2 when the nematic directors of the infiltrated LCs are orientated at random. Basically, complicated photonic bands in PhCs display strong spatial dispersion (diffraction properties) and anisotropy, which can lead to many interesting phenomena such as superprism effects, negative refraction, and self-guiding. Spatial dispersion reveals itself in a variation of the light propagation direction as a function of frequency. On the other hand, temporal dispersion relates to the change in the phase index of an optical medium as a function of frequency. If spatial dispersion and temporal dispersion are both considered, it is not easy to obtain the band structure and the corresponding CFCs of a PhC. However, the LC birefringence in the infrared region is nearly

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independent of frequency so that the temporal dispersion can be ignored to simplify the simulations [12]. In this study, two kinds of incident lights with the normalized frequencies ω=0.27 and ω=0.3 are adopted to investigate the transmission properties for different orientations of LC directors. The former is in the band gap near Band II, and the latter is near the band edge of Band II.

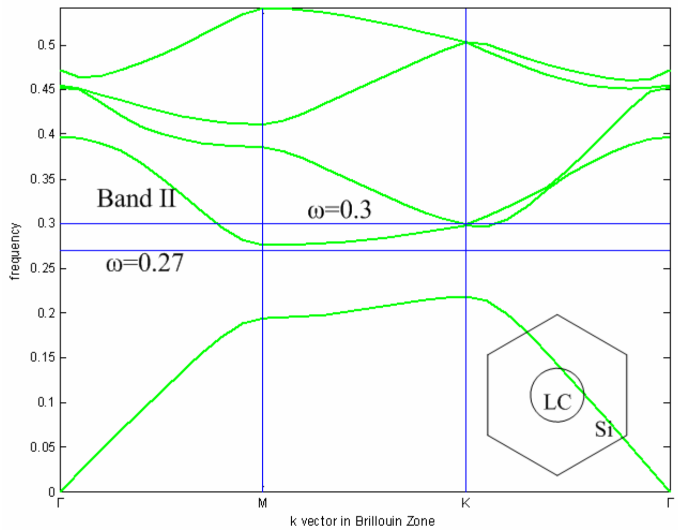

Fig. 2 Calculated photonic band structure (TE polarizations) for the triangular 2D PhC infiltrated with LCs. The inset shows a view of the triangular lattice with the unit cell. The refractive index is approximated to be isotropic within the pillars when directors are oriented at random. The normalized frequencies marked for ω=0.27 and ω=0.3 are adopted to investigate the phenomena of the partial band gap and the anomalous refraction.

Our first test structure was found to exhibit the partial band gap effect at ω=0.27. In the case of applying an external field, Fig. 3 shows the CFCs of Band II for the LC directors orientated at Φ=0° and 90°. In Fig. 3(a), if a vertical (horizontal) construction line is drawn at the position $k_x/b_2=0$ ($k_y/b_2=0$), the intersection points can be obtained between the line and the contours of ω=0.27. In the case of Φ=0°, incident light will penetrate the PhC. As the directors are orientated at Φ=90°, these contours shown in Fig. 3(b) are shifted to the diagonal positions. Light will reflect back because the specified construction line without any intersection point falls into the partial band gap. A schematic drawing for a normal incident light is shown in Fig. 4 when an in-plane electric field is applied. The transmission of PhCs changes from the "on" to the "off" state when an external electric filed is applied at different directions. The FDTD method is used to simulate the light propagation in the PhC, and the results can be compared with the theoretical prediction by a CFC analysis. Corresponding to ω=0.27 for a=1μm, a Gaussian wave with the center wavelength λ=3.7μm is taken as an input. Figure 5 shows the transmission spectra of the observing point. In Fig. 5(a), the short wavelength gap edge for Φ=0° is at 3.8 μm, and the ratio of outgoing to incoming power at λ=3.7μm is about -6db for the on-state transmission. In Fig. 5(b), the short wavelength gap edge for Φ=90° is shifted to 3.6 μm and the off-state transmission ratio at λ=3.7μm is about -50db. The effect due to the variation of LC directors is obvious. An optical switch based on the partial band gap effect can be obtained by rotating the directors with an in-plane electric field. For a=0.4185μm at the same normalized frequency, an optical switch for telecommunication wavelength (λ=1.55μm) can be designed to achieve a theoretical contrast ratio of 200:1(23dB) between switching on and off. The transmission normalized with respect to the incident amplitude is shown in Fig. 6.

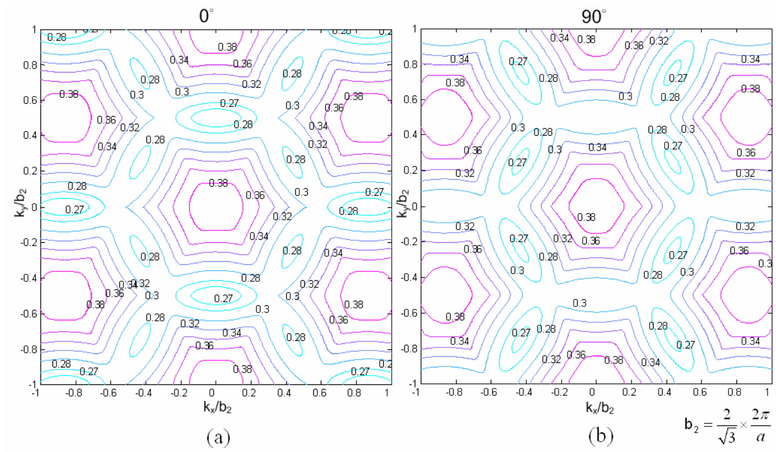

Fig. 3 The CFC representation of $\omega(k_x,k_y)$ in the frequency range of Band II, with the contours for LC directors orientated at (a) $\Phi=0°$ and (b) $\Phi= 90°$.

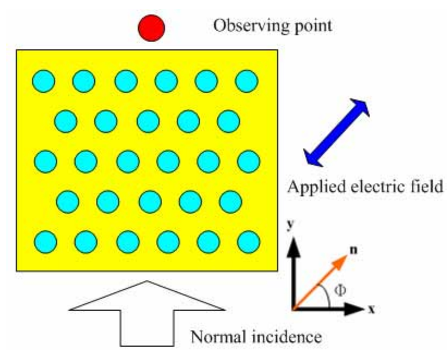

Fig. 4 Schematic diagram for the case of a normally incident Gaussian wave when the orientation of LC directors is varied by an in-plane electric field.

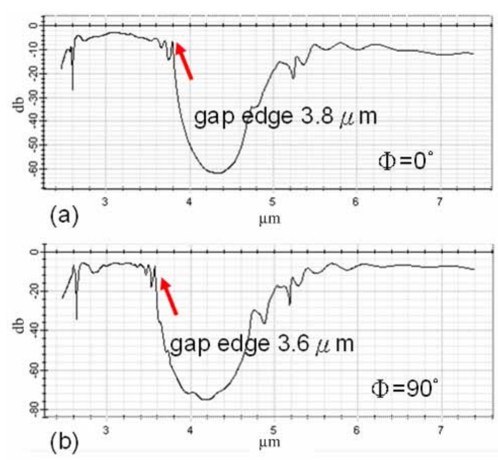

Fig. 5 Theoretical spectral responses calculated from the observing point (shown in Fig. 4) by the FDTD method. The input TE-polarized light is a Gaussian modulated wave with the center wavelength $\lambda=3.7\mu m$ corresponding to $\omega=0.27$ for $a=1\mu m$. The LC directors are oriented at (a) $\Phi=0°$ and (b) $\Phi=90°$ to show the shift of the partial band gap when an in-plane electric field is applied in different directions.

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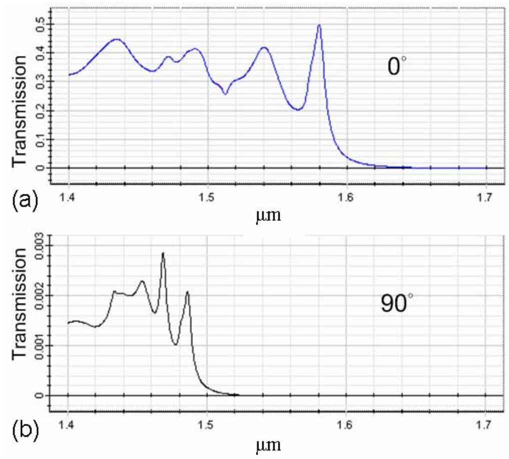

Fig. 6 TE-polarized transmission spectra calculated from the observing point (shown in Fig. 4) by the FDTD method. The input light is a Gaussian modulated wave with the center wavelength λ=1.55µm corresponding to ω=0.27 for a=0.4185µm. The LC directors are oriented at (a) Φ=0° and (b) Φ=90° for the "on" and the "off" states, respectively.

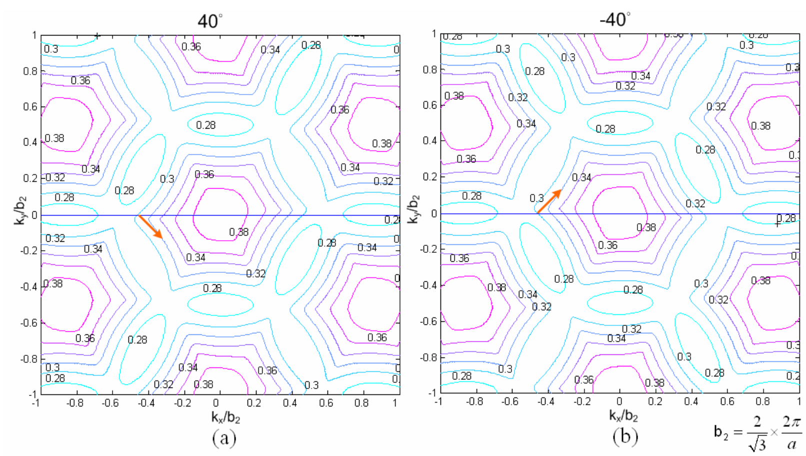

Fig. 7 The CFC representation of $\omega(k_x,k_y)$ in the frequency range of Band II, with the contours for LC directors orientated at (a) Φ=40°and (b) Φ=-40°. The arrows stand for the group velocity vectors determined by the gradient $\nabla_{\mathbf{k}}\omega$. These directions are selected by the solid lines, which are derived based on the conservation of the parallel wave vectors (k_y=0).

Another test structure was found to present the anomalous refraction behavior at ω=0.3. Figure 7 shows the CFCs of Band II for the LC directors orientated at Φ=40° and -40° when an external electric field is applied. The incident edge is set normal to the Γ-M direction (normal to the *x*-axis). The energy propagation direction in 2D PhCs is oriented in the direction of the group velocity vector $\mathbf{V}_g=\partial\omega/\partial\mathbf{k}$, which is always perpendicular to the CFC and points towards increasing values of frequency. The tangential components of wave vectors of incident waves and refractive waves are always conserved across the interface between two materials. A construction line which indicates the momentum conservation can be set up to determine the group velocity direction at the intersection with the CFCs. For a normal incident light, the arrows in Fig. 7 indicate the directions of light. In Fig. 7(a), LC directors are orientated at Φ=40°, and the light propagation direction is refracted at

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approximate -45° to the k_x-axis direction. In Fig. 7(b) for Φ=-40°, and the refractive angle is about 45°. Changing the LC directors, which leads to the distortion of CFCs of the PhC, could shift the maximum deflection angle by ~90°. Beam-deflection-type switches could be accomplished via the large variation of deflection angle. In addition, the FDTD method is also used to investigate the tunable refraction effect. Figures 8(a) and (b) display the magnetic field maps of propagating waves at Φ=40° and -40°, respectively. The arrows indicate the light propagating directions. The field patterns show that the refracted angles for the TE polarization are about -29° and 28°, respectively. The FDTD simulations clearly verify that the light propagating direction can be altered by rotating the LC directors, even though the refracted angles determined from the FDTD method are not in very good agreement with those determined from the CFC analysis. The finiteness of the system and the effect of the Goos-Hänchen shift result in the mismatch between the employed numerical methods [21].

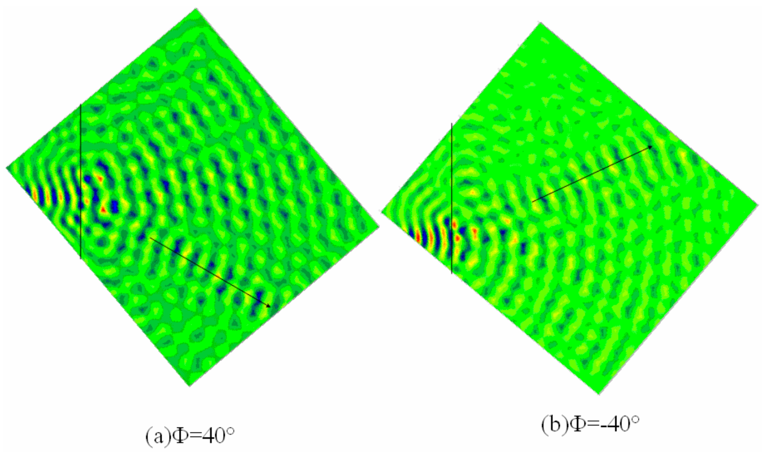

Fig. 8 FDTD simulations for the distribution of the magnetic fields. For the condition of the normal incidence with the frequency ω=0.3, the LC directors are oriented at (a) Φ=40° and (b) Φ=-40° to show the anomalous refraction effect when an in-plane electric field is applied in different directions. The arrows highlight the direction of the energy of the output wave. The refracted angle for Φ=40° (Φ=-40°) is about -29° (28°).

5. Conclusion

The concept and operation for the triangular 2D PhC infiltrated with LCs have been demonstrated at different transmission properties. Via the CFC analysis and the FDTD method, two mechanisms based on the PhC characteristics of the partial band gap effect and the anomalous refraction phenomenon have been used to design the optical switches: "on/off" type switch and beam-deflecting-type switch. The corresponding required conditions for different working statuses are derived. Simulation results reveal that the switches using tunable PhCs can be operated, provided that the operation frequency and the incident direction are carefully determined. Altering the direction of LC directors with an external field could control the light transmission from the "on" state to the "off" state or could manipulate a single beam refraction from one side to the other side with a maximum deflection angle ~57°. In summary, the PhC infiltrated with LCs is such a versatile device that combines the PBG, anomalous refraction, and polarization switching. It is believed that many potential applications can be found in optical communications.

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