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Electro-optical tenability properties of defective one-dimensional photonic crystal

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ABSTRACT

In this work, the optical transfer matrix formalism was applied to study the linear electro-optic effect on perfect and defective one-dimensional photonic crystal (1D-PC) composed of lithium niobate and polymer (polystyrene) multilayers. The effects of an external electrical field on the reflectance spectra of the proposed PCs were studied as a function of the angle of incidence and the types of polarization (TE and TM waves). The results show that, at a constant angle of the incident, the PBGs are shifted to shorter wavelengths for both TE and TM waves as the applied electric field increased. The position of defect mode decreases linearly from 1.401 to 1.379 μm for TM wave and from 1.398 to 1.377 μm for TE wave as the applied electric field increased from 0 to 100 v/μm at an angle of incident 50°. By increasing the angle of the incident from 0 to 50 ° at constant applied electric field, the position of PBG for both TE and TM are shifted toward the shorter wavelengths. In addition, the width of the PBGs of TE wave is increased from 0.334 to 0.358 μm and the width of the PBGs of TM wave is decreased from 0.334 to 0.248 μm at 100 v/μm. This study may be valuable for designing tunable photonic devices with driving electrical field, which has potential applications in the area of photonics and optoelectronics.

1. Introduction

Photonic crystals (PCs) are periodic structures with alternating refractive indices in one, two, or three dimensions with periods comparable to the wavelength of the incident light [1]. In recent years, the studies of the electromagnetic propagation in the photonic crystals have become intense research area due to their novel applications in modern optical devices. PCs can be used to control the propagation of light by the appearance of a photonic band gap (PBG) and photon localization [2,3]. PBG is wavelength interval in which electromagnetic waves cannot propagate through the PC because the waves will undergo exponential decay (evanescent mode) and total reflection. The photon localization can be derived inside the PBG by adding a defect layer into the PC to break the periodic feature [4]. When the incident photon wavelength is equal to the defect-state wavelength, the photon will be localized in the place of the defect and a resonant transmission peak is generated within the PBG. The PBG and defect mode are strongly depending on some parameters such as index contrast, layer thickness, the state of polarization, filling fraction, and angle of incidence [5–7]. Hence, any variation in the refractive index of the PC can produce a significant modulation in the position of the defective mode. This modulation can be used as an indicator for measuring the index change.

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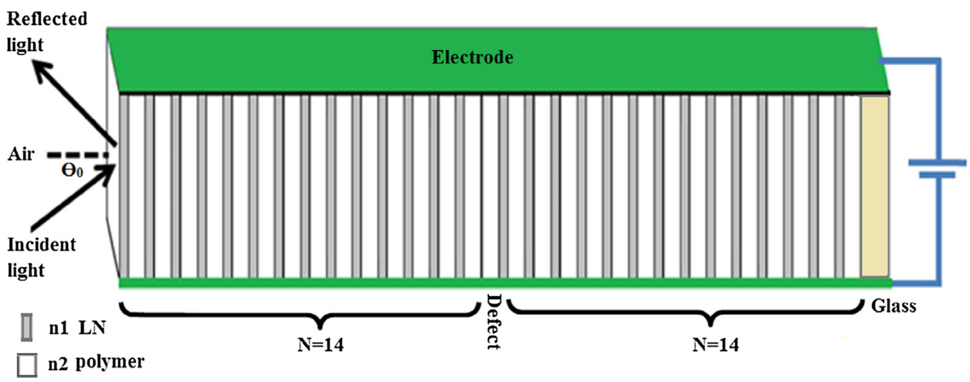

Fig. 1. Schematic diagram of the proposed 1D-PC with a defect layer under the effect of an external electric field.

Table 1
The values of the different parameters that used in the calculations.

	$LiNbO_3$ (Material 1)		Polymer (Material 2)
Refractive index (λ in μm)	$n_1 = \sqrt{A + \frac{B}{\lambda^2 - C^2} + \frac{D}{\lambda^2 - H^2} - F\lambda^2}$	A = 5.35583; B = 0.100473; C = 0.20692; D = 100; H = 11.34927; F = 153.34; [20]	$n_2 = 1.6$ [21,22]
Electro-optic coefficient (10^{-6} μm/V)	$\gamma_1 = 30.9$ [23]		$\gamma_2 = 150$ [21,22]
Thickness (μm)	$d_1 = 0.1813$		$d_2 = 0.2421$

On the other side, certain materials can change their refractive indices under the exposure to external physical signals such as electrical, magnetic, thermal, acoustic, or mechanical signals. The electro-optic (EO) effect is a change in the optical properties of the material, especially its refractive index, in response to an external electric field. This effect occurs due electric field causes a redistribution of bond charges and possibly a slight deformation of the crystal lattice [8]. Therefore, the inverse dielectric constant (impermeability) tensor changes accordingly. Then, the EO effect can be used for the dynamic control of the refractive index. Also, the EO materials play a significant role in many practical applications such as optical communication systems, charge storage, optical sensors, electroluminescent devices, and optical computers [9–11]. Lithium Niobate (LN) and polymers (such as polystyrene) are typical electro-optic materials. The LN is a nonlinear ferroelectric material widely used in optoelectronics and surface acoustic wave devices [12,13]. Then, the design of LN photonic crystals can potentially decrease the size of the critical components in many optical systems [14]. Moreover, the EO polymers gained an increased interest for telecommunication applications due to their low optical losses in the 1.3 and 1.55 μm telecommunication windows. Also, these polymers are characterized by high linear EO, low processing cost, and reliable mass production [15]. Therefore, it is imperative to study the effect of the external electric field on the PBG and photon localization of a PC from LN and a polymer such as a polystyrene.

Most previous studies were focused on design and fabrication of 2D-PC structures for EO applications by etching hexagonal or square arrays of holes in LN or polymer film [16,17]. However, there are practical limitations for obtaining highly ordered 2D-PC because the difficulty of fabricating deep and cylindrical holes in bulk crystals. Also, PBG structures may be destroyed when a large number of defects or disorders are introduced in the PC [18]. Then 1D-PC structure (such as multilayer films) can be used as a real alternative for 2D-PC because it can be simulated and fabricated more easily than 2D-PC [19]. Moreover, it can be easily adapted for use in many applications. Here, an EO structure based on 1D-PC ($LiNbO_3$/polymer multilayers) with a defect layer is proposed. Using transfer matrix method (TMM), the reflection at different applied electric fields and incident angles for both transverse electric (TE) and transverse magnetic (TM) modes are calculated and discussed.

2. PC design

To have an idea about the effect of the electric field on the optical spectra of PCs, a 1D-PC from alternately stacked LN and polymer layers with refractive indices n_1 and n_2 respectively is addressed. The LN layer is inserted as a defect layer. The PC is surrounded by air and glass substrate. The modeled structure was based on the following configuration: air/$(n_1n_2)^N$/n_2/$(n_1n_2)^N$/glass with N = 14 period. Also, two electrodes are placed on the sides of the PC to apply an electric field. Schematic diagram of the proposed structure is shown in Fig. 1. The physical thicknesses of $LiNbO_3$ and polymer are taken according to the quarter wave arrangement at the operating wavelength in the infrared region $\lambda_0 = 1.550$ μm, which is essential for the optical communication. The period of the lattice is $d = d_1 + d_2$. The values of the different parameters that used in this study are given in Table 1.