Optik - International Journal for Light and Electron Optics 168 (2018) 839–846

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.com/locate/ijleo

Original research article

Use of uniaxial ferroelectric material as a tunable double-optical filter based on polarization converter and splitting in photonic crystal

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ARTICLE INFO

Keywords:
Photonic crystal
Ferroelectric
Beam splitters
Optoelectronic

ABSTRACT

We have investigated the tunability of splitting, intensity and polarization conversion of the double optical filter in a one-dimensional photonic crystal (1DPC) structure containing anisotropic ferroelectric material, based on the Pockels effect. A 4 × 4 transfer matrix method has been used to investigate the optical properties of the proposed structure at oblique incidence of light with S polarized wave. The influences of the external electric field, and incidence angle on the tunability of the transmission and polarization conversion of the optical filter, will be investigated. Numerical results exhibit that large splitting and blue shifting of the defect modes can be achieved in the presence of the external electric field and incidence angle, respectively. Also, the results reveal that by the application of an external electric field to the anisotropic layer, for an incident plane wave with (S)-polarization, two transmitted wave containing both P and (S)-polarized wave is created. Moreover, by increasing the external electric field and incidence angle, the edges and wide of photonic band for two transmission coefficient T_{SS} and T_{SP} can be modulated.

1. Introduction

Photonic crystals (PCs), which are materials with periodic modulation of their refractive index on the scale of optical wavelength [1], have been studied extensively since Rayleigh investigated them in 1887 [2]. A photonic crystal (PC) structure is a periodic array of two or more materials having different electrical or magnetic constants. Interest in this array has increased in recent years because of its electromagnetic properties and its ability to control the propagation of electromagnetic waves [1,2]. Controlling and manipulating the propagation of light are some of their usages in these days [3,4]. Different arrangements of 1DPC structures have attracted attention because it can be easily fabricated by modern experimental methods. The most important feature of a PC structure is the photonic band gap (PBG) which is the range of wavelengths that incident light cannot propagate through the structure. It is well known that introduction of an extra element in to the regular photonic structure destroys the periodicity and leads to the appearance of a narrow peak with high transmission at a frequency inside the PBG, the so-called defect mode, which can be employed to optical filtering [5–10].

Tunability of the optical filter in photonic structures is a key feature required for the dynamical control of light transmission of the photonic crystal devices. In general, the transmission of light through photonic crystals depends on the geometry and the compositional parameters. When a PC structure is constructed, its optical or physical properties cannot be changed, physically. In fact, by

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https://doi.org/10.1016/j.ijleo.2018.05.007
Received 30 March 2017; Accepted 2 May 2018
0030-4026/ Published by Elsevier GmbH.

using the materials with externally tunable optical or physical properties in a PC, it would be possible to change the optical spectrum of the structure. The electric permittivity or magnetic permeability can be modified using external factors via electric field, a magnetic field, temperature, and pressure. The tunability of spectral properties makes the PC structure appropriate for design of basic elements for use in modern optical devices [11–14].

Various schemes have been proposed to demonstrate a tunable optical filter made of PC, but tunability by application of an electric field has a fast response compared with magnetic, thermal, and mechanical tuning [15–17]. It has been shown that the electric field applied can be used to tune the photonic band gap in the PC. The effect of the external electric field on the properties of the defect mode, comprising the peak position and optical bistability has been investigated [18–21]. Recently, much attention has been paid to the PC structures and structures that are more easily tunable by external factors with high degree of freedom. Anisotropic PCs are a new type of photonic crystals have high optical sensitivity to parameters such as optical axis direction, the direction and type of field polarization, and electric or magnetic field intensity. Unlike the conventional isotropic medium, the relative permittivity and/ or permeability of the anisotropic materials are described by tensors instead of scalars, which makes the media exhibit different behaviors and gives rise to a lot of interesting electromagnetic phenomena, such as birefringence, polarization rotation, and polarization [22–25]. For such applications, it is advantageous to achieve tunability through the electro-optic effect, for which the intrinsic response speed is known to be in the visible range. The electro-optic effect is one of the interesting characteristics of ferroelectric materials. The refractive index of a ferroelectric material can be modulated by applying an external electric field. Therefore, it is expected that index-tunable PCs can be realized if one fabricates PCs by using ferroelectric materials. The anisotropy of electro-optical materials and their optical properties change easily from the Pockels effect [26–28].

Also, in anisotropic photonic structure with arbitrary orientation of principal axis of the anisotropic layer, each incident plane wave with *S* or *P* polarization produces two reflected and two transmitted plane waves containing both S and P polarized plane waves [29–33].

In this Letter, we present a new narrowband double-optical filter is proposed combined of two-symmetric PCs formed by alternating two isotropic dielectric layers and anisotropic ferroelectric material as a defect layer that provides double narrow peaks in transmission, at oblique incidence of light. In this case, we used the 4×4 transfer matrix method to study the tunability of polarization conversion, splitting, controlling the number and transmitted intensities of optical filters in a PC structure containing anisotropic electro-optical materials. We show that double-tunable optical filter as well as polarization conversion can be achieved simultaneously in the proposed structure. Also, in this paper, effects of the external electric field and incidence angle, for a specified value of orientation of the optical axis of the anisotropic layer on the number, splitting, peak position, and intensity of optical filter have been investigated. It is well known that the application of external electric field in certain direction and opposite optical axis anisotropic layer leads to the appearance off-diagonal elements in the electric permittivity matrix that depends strongly on external electric field intensity. We found that the tunability of peak wavelength is critically dependent on the off-diagonal elements. The peak wavelength of the defect mode splits in to two modes if the external electric field is applied to electro-optic anisotropic layer. Therefore, the existence of off-diagonal elements in the electric permittivity tensor of anisotropic materials has a great effect on the tunability, splitting and conversion of wave polarization.

The organization of this paper is as follows. The 4×4 transfer matrix method for1D-PC single containing electro-optic anisotropic layer, for oblique incidence of light, is deduced in Sec. 2. The numerical results and the effect of the applied electric field and incidence angle on tunability of the optical filter are illustrated in Sec. 3. The conclusion is presented in Sec. 4.

2. Models and theory

Consider a general anisotropic medium with its planar interface parallel to the x−y plane and its normal parallel to the z− axis, as illustrated in Fig. 1. The structure was composed of two isotropic dielectric layers with permittivity ε_A and ε_B with corresponding thicknesses d_A, d_A and C denote the anisotropic electro-optical material as a defect layer with an arbitrary optical axis. The optic axis perpendicular to the periodicity direction (z). The layers were arranged as $(BA)^m C\ (AB)^m$ to construct a symmetric PC structure,

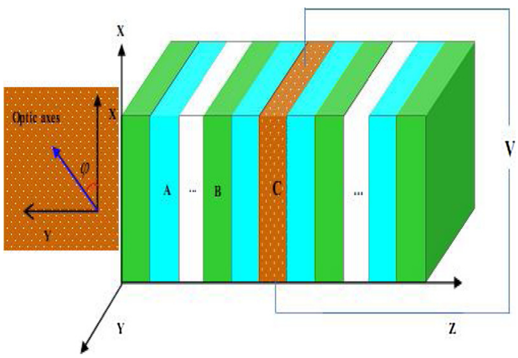

Fig. 1. the scheme of the proposed 1D defective PC structure composed of an anisotropic defect layer with externally applied voltage in the *x* direction.