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Invited Paper

Two dimensional tunable photonic crystal defect based drop filter at communication wavelength

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ABSTRACT

We propose a two dimensional photonic crystal (PhC) based drop filter, at communication wavelength with more than 90% transmission. The filtering is achieved by introducing two line defects and three point defects in a two dimensional triangular array of ferroelectric rods in air. Using the electro-optic property of the ferroelectric, about 32 nm tuning in the resonance wavelength is obtained. For the calculation of transmission, finite difference time domain (FDTD) simulations were performed. The operating frequency range is explored via the band structure which is obtained by the implementation of plane wave expansion (PWE) method. The influence of the radius of various rods on the filter wavelength as well as efficiency is also analyzed. The different possible configurations of this filter are also considered.

1. Introduction

Two dimensional (2D) PhC is a periodic arrangement of two materials with different dielectric constants in two directions. PhC will not allow a particular set of frequencies to pass though it and are said to have photonic band gap (PBG) [1]. However, these devices can be made to allow some frequencies within the PBG to pass through them by introducing some kind of defect in a perfectly periodic structure. Using the fact of implementation of defects in PhCs, various communication components and devices were proposed theoretically and realized experimentally [2]. Among these, filters are one of the essential elements of photonic circuits. They are necessary in designing the wavelength division multiplexing systems by selecting a channel or number of channels [3]. PhC is considered as an ideal base for designing filters due to its unique PBG and good light confinement effect [4]. The different photonic crystal based filters like add-drop filters [5], channel drop filters [6,7], band pass and stop filters [8–11], etc., have been proposed and realized experimentally.

The channel drop filters are essential part of the photonic communication systems and optical integrated chips [12]. They selectively transmit, one wavelength among a set of wavelengths of wavelength division multiple optical signal, and considered as a suitable candidate for the channel drop in wavelength division multiplexing systems. The channel drop filters in photonic crystals are obtained by utilizing the coupling of modes between the micro-cavities and waveguides. The waveguides and resonant cavities are made via introducing the defects. There are many proposed drop filters which considers photonic crystal as a suitable platform [13–15].

Some of these are tunable filters, whose channel wavelength can be controlled by external means. These are of different materials and working principles, which find a different role by giving an additional advantage of tuning [16]. Among this, the electro-optic tuning has a great interest, due to its fast response [17,18]. But these kind of 2D PhC filters at communication region have rarely been proposed due to the poor tuning efficiency of ferroelectric in these regions, compared to the microwave region [19]. However, there are some devices based on materials like $LiNbO_3$ [20] which gives good tuning in optical frequencies also [21]. Recently, Fu et al. [21] realized a multi channeled filter by photonic crystal with square lattice arrangement of air holes in an electro-optic material, barium titanate ($BaTiO_3$). The $BaTiO_3$ has a huge electro-optic coefficient and is said to be ten times greater than that of $LiNbO_3$ [22]. Further it is regarded as transparent for near infrared and visible frequencies [22]. There are some fabricated micro-structures based on barium titanate pillars with nano scale radius [23]. Here, we have selected triangular lattice arrangement of $BaTiO_3$ rods in air background, for the realization of a tunable drop filter. The 2D photonic crystal provides larger PBG for triangular lattice, when compared to the square lattice [24]. Moreover, the rod type PhCs are preferred due their low loss, compared to the hole type PhCs. These rod type PhCs are adaptable with the optical integrated circuits and can be easily fabricated [25].

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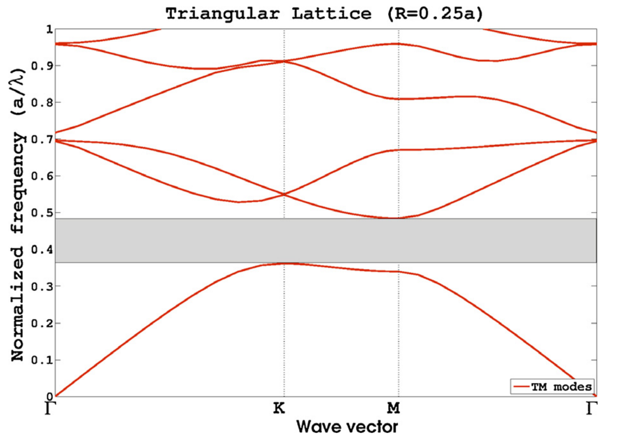

Fig. 1. Band structure for TM mode of perfectly periodic two dimensional triangular lattice of rods in air.

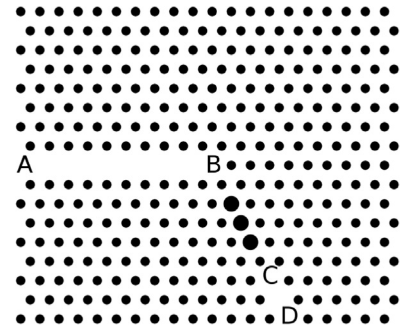

Fig. 2. PhC defect based optical filter design.

This paper studies a 2D photonic crystal drop filter, which has been analyzed theoretically by introducing three point defects and two line defects, in a periodic structure as shown in Fig. 2. The two line defects, AB and CD were obtained by removing the existing ferroelectric rods. The three point defects were introduced by placing the rods of higher radius of the same material. These three point defects serve in selecting the resonance at communication wavelength, 1.5 μm. The chosen waveguides and defects, forms an angled geometry instead of straight alignment. This provides a reflection feedback, which enhances the drop efficiency [26]. The similar technique has been suggested and the proper mechanism of operation and the conditions for enhancing drop efficiency are investigated by Kim et al. [26]. We have used ferroelectric rods which result in tuning of the filter by the application of electric field, adds an advantage. The tuning is obtained about 32 nm. Additionally this electro-optic tuning of the resonance wavelength can be used to compensate the fabrication errors. In our calculation PBG is analyzed by PWE method [27], and FDTD [28,29] simulation were done to study the filter characteristics.

2. Theory

In ordered to realize the PhC filter, we have considered a two dimensional triangular lattice arrangement of ferroelectric rods in air. The periodicity a of the lattice is 684 nm, where periodicity refers to the distance between centers of two nearest rods. The dielectric rods have radius of 0.25a. The refractive index of the background is taken as 1. The refractive index of the ferroelectric rod in zero applied is $n_0 = 2.3$ [21]. The field dependent refractive index of $BaTiO_3$ is given by [30]

$$n_f = n_0 + \frac{\gamma_{eo} n_0^3 V}{2L} \quad (1)$$

where γ_{eo} is the electro-optic coefficient and is 360 pm V^{-1} [22]. L is the gap between two electrodes and it is set to be 2 μm [30]. V refers to the voltage given, which should be less than the break down voltage and is 60 V for $BaTiO_3$ [31,32].

Fig. 1 sketches the band structure of the considered triangular lattice PhC without any defect. Band structure was constructed by PWE method [27]. The figure shows band structure for TM mode, which has a PBG in the normalized frequency range 0.362–0.485a/λ. This corresponds to the wavelength region 1238–1657 nm which includes, communication wavelength of 1.5 μm.

The channel drop tunneling phenomenon will occur, when two waveguides with continuum of propagating modes, are placed closely with a resonator mechanism that supports the localized modes. That is, the propagating modes can be exchanged between the two waveguides through this kind of system. The change in symmetry of the resonant state affects the transmission properties. So by managing the symmetries, an optimal transmission can be achieved. The number of localized states of resonator also has a significant role in manipulating the optical properties [33]. In ordered to understand the transmission of electromagnetic wave in drop filter, the temporal coupled mode theory can be applied [34,35]. This theory is well described for different systems in Refs. [26,36,37].

To obtain the filter, we have introduced the following defect in the perfectly periodic structure as shown in Fig. 2. There are two line defect waveguides (AB and CD in Fig. 2) and a cavity with three defect rods. We have created the waveguide AB and CD inside the PhC by removing the ferroelectric rods. From the section BC, the middle three rods were replaced with rods of same material but having different radius, keeping the two end rods as it is. These ferroelectric rods which form the cavity have the radius of 0.417a. Thus photonic state within the PBG region, which is in resonant with the defect is appeared. By properly designing the device with control of the radius of defect and other rods, we are able to obtain the filter at 1.5 μm. That means, we have optimized the structure (radius of defect as well as other rods, number of defect and distance between the rods) to get this wavelength with good quality factor and with >90% drop efficiency (transmission). In general, the increase in number of defect will improve the quality factor, but it will decrease the transmission [38]. The chosen number of defects are optimal for the achievement of better filtering of the radiation at 1500 nm in this particular structure.

We have used FDTD method for the filter transmission calculations [28], adopting FDTD based software MEEP [29]. Perfectly matched layers (PML) with thickness, 10a used as boundary conditions. Gaussian with center of frequency 0.4234a/c and width 0.15a/c is used as source.

3. Results and discussion

The filter design is as given in Fig. 2. The light with a range of wavelength from 1450 nm to 1650 nm is incident from the left into the waveguide AB. From this, only 1.55 μm is filtered out though the other waveguide CD, and all other wavelengths were reflected. That is, only the resonant wavelength corresponding to the defect is coupled to the waveguide CD, through the cavity of three rods. Fig. 3 shows transmission verses wavelength plot of the designed filter in the wavelength range of 1450–1650 nm. We can see a single peak with center of wavelength, λ_c at 1.55 μm with more than 90% output transmission efficiency. This has band width ($\delta\lambda$) of 14 nm where, band width is the measure of full width at half maximum. The quality factor (QF = $\lambda_c/\delta\lambda$) [39] of this filter is about 110. Fig. 4 shows, the electric field profile of the filter for the wavelength of 1.55 μm.