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Studies on photonic bandgap tuning of GaAs photonic crystal waveguide by thermo-optic effect

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Dedicated to Prof Anurag Sharma, FNA for his numerous contributions to Optics and Photonics

In this article, design of a photonic crystal waveguide in hexagonal lattice structure is presented and the effects of temperature on photonic band gap and band edges are studied. Thermo-optic effect is employed to consider the variations in the refractive index of the slab material. Temperatures ranging from 10 K – 100 K and 300 K – 400 K were considered for this purpose. Simulations were performed in MIT Photonic Bands to calculate the eigen frequencies of the structure. The bands are shifting linearly with change in temperature. The structure is designed to get the eigen frequencies in the conventional band (C-band) and long wavelengths band (L-band) of the communication windows. The proposed structure may be used as a temperature sensor, optical trip switch, and wavelength filter.

Keywords: Photonic crystal Waveguide, Bandgap structures, Temperature sensor, Thermo-optic effect, MPB.

1 Introduction

Photonic crystals (PCs) are attractive due to their wide range of applications in light modulation and control [1-5]. These are the periodic structures made of dielectric materials. The main applications of PCs in waveguides have been reported as slow light devices, nonlinear parametric amplifiers, wavelength filters and optical sensors [6-12]. PCs are fabricated by drilling air holes in the dielectric slabs and by creating parallel dielectric cylinders on a substrate. The ability to control the light in the PC originates from its geometry and the refractive index (RI) of the material from which it is made up of [13]. One can produce diversified applications by engineering PC's geometry, which is the chief tool in PC technology. Photonic crystal waveguides (PCWs) are the waveguides formed by eliminating one row of air holes/cylinders from the PC structure. They find futuristic applications in the light control and modulation. In this article, we analyse the features of PCW based on thermo-optic effect.

Geometry has a great influence on the performance of the PCW. Different structures lead to different working frequencies, differences in parameters like group velocity, dispersion and characteristics of PCW [14-17]. This provides the opportunity to tune the photonic bandgap (PBG) for various applications. Though the tuning of the PBG exists from several years [18-22], it is always interesting because of its unique design flow. Depending on the requirements, one can design the application specific structure, whose PBG is fully controlled by its geometry and effective RI [23-25]. PBG is primarily tuned by engineering the dispersion features of the PCW. The majority of the designs in the literature involve geometrical engineering, embedding liquid crystals and applying external heat, electric and magnetic fields [18,26-27]. The aim of these external fields and filling with liquid crystals is to alter the effective RI, which can tune the PBG.

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In the present work, we made an attempt to design a PCW which can be used for applications like temperature sensor, optical trip switch, and wavelength filter. For the proposed structure, Gallium Arsenide (GaAs) is used as the base material. In the GaAs slab, air holes in hexagonal lattice are considered to form the PCW. The study was carried out at two different temperature ranges 10 K – 100 K and 300 K – 400 K. Thermo-optic effect is used to calculate the RI and dielectric constant of the slab at lower and higher temperatures. It may be a novel approach to use thermo-optic effect for studying the PCW. Calculated refractive indices and dielectric constants were used during the simulations by MIT Photonic Bands software (MPB). The output of these programs provide the eigen frequencies of the structures, which were analysed further to find the band edges and operating wavelengths of the structure. We focused to obtain the eigen frequencies in the C-band and L-band for various applications of the structure.

2 Theoretical Design

The proposed PCW has a lattice constant (a) of 304 nm. Air holes of radius 0.18a were arranged in a hexagonal lattice to form the periodic structure in GaAs slab of thickness 240nm. A row of air holes is removed to form the waveguide of width 1.64a. The geometrical parameters are calculated to make the PBG as small as possible and to generate various applications based on narrow band. Figure 1 shows the schematic of the proposed design. In the present study, we have used Eq (1) given below to calculate the RI and the corresponding dielectric constants of the slab with applied temperature.

According to McCaulley *et al* [28], the RI of GaAs at near infrared regions is given by

$$n(T) = n(T_{ref})\ \exp[(T - T_{ref})\beta] \tag{1}$$

where T corresponds to the temperature of the sample, T_{ref} corresponds to the reference temperature, and β represents the temperature coefficient or thermo-optic coefficient of the material. For the present work, T_{ref} is chosen as 300 K, and β is taken as 2.25×10^{-4} K^{-1}. Using Eq (1), the RI of GaAs is calculated in the temperatures range of 10 - 100 K and 300-400 K in near-infrared regions. These RI values are used for the simulations to calculate the eigen frequencies of the structure.

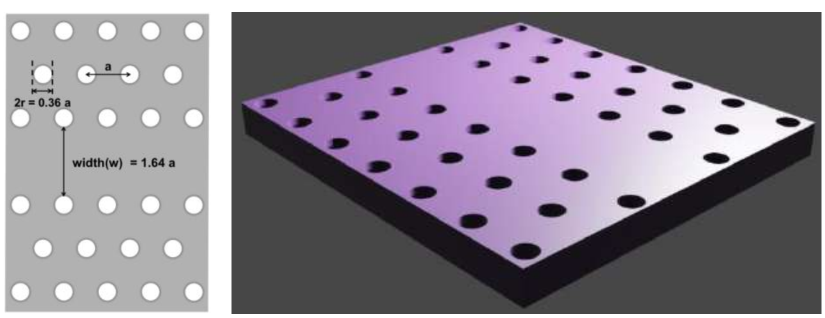

Fig 1. Schematic of the proposed PCW

3 Results and Discussion

Figure 2 shows the complete 3D photonic band diagram of the proposed structure. The preliminary observations confirm the presence of PBG between band 7 and band 8 for both transverse electric (TE) and transverse magnetic (TM) modes. The geometrical parameters are optimized to make the narrow down of the PBG. These narrowband structures are interesting because of their applications in wavelength filters, sensors and switches.

The calculated PBG for the structure is 0.4134% for TM modes and 5.017% for TE modes. This bandgap is shown in the Figs 3 (a & b). TM Field distribution at band 7 and band 8 is shown in Fig 3 (c).

The simulations were performed at low temperatures and at high temperatures ranging from 10 K to 100 K and from 300 K to 400 K to calculate the eigen frequencies of the structure. To make further analysis, the lattice constant of the structure, and eigen wavelengths were calculated.

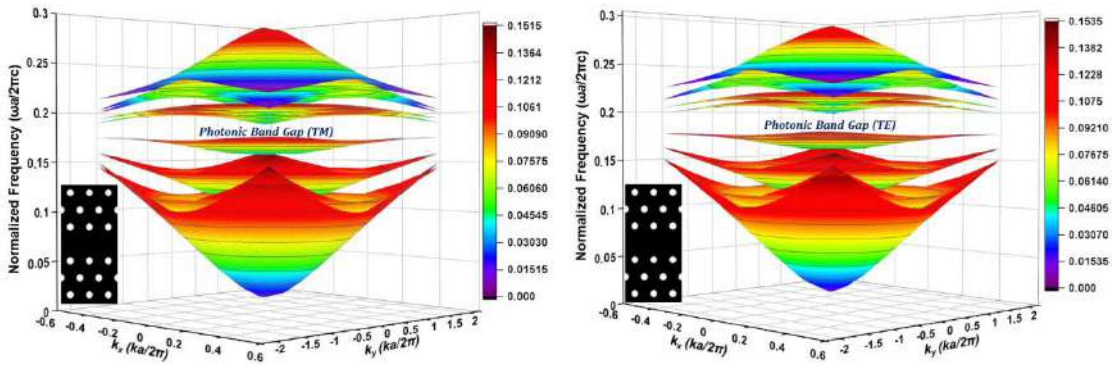

Fig 2. 3-D Photonic band diagram of the simulated structure. Bandgap diagram for (a) TM modes (b) TE modes.

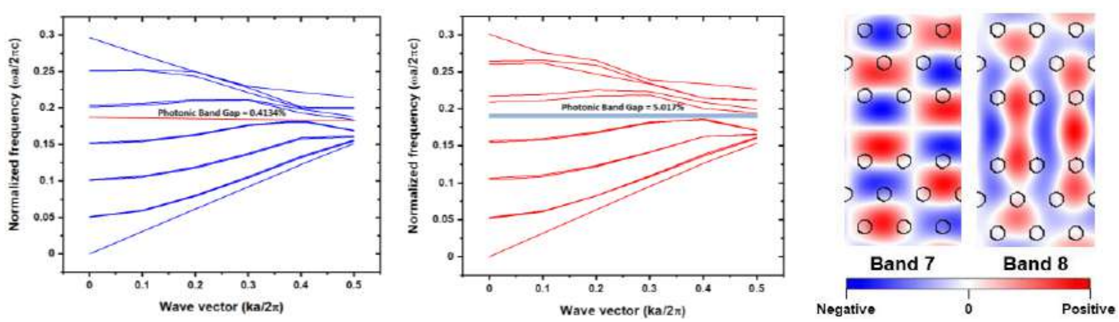

Fig 3. 2-D Band diagram of the structure. (a) TM modes (b) TE modes (c) TM Field distribution at band 7 and band 8.

The obtained output from the simulations is normalized data, and needs to employ the lattice constant to calculate the eigen frequencies and eigen wavelengths. To observe the bands in the communication wavelengths, (as many sources are available) the lattice constant is calculated and is found to be 304 nm for the present structure. As the PBG exists between band 7 and band 8, the frequency and wavelengths corresponding to these bands are calculated. Further the calculations were performed at the selected temperature ranges.

Figure 4 shows the change in eigen wavelengths corresponding to the change in temperature. The plots are linear, which recommends the possible application of proposed structure as a temperature sensor for both lower and higher temperatures. In addition to this, the change in wavelength with change in temperature is observed in the range of 0.3562 – 0.4199 nm/K which is a good sign of high sensitivity. This sensitivity is very higher than that of various optical sensors. The plots in Fig 4 represent the band edges of the PBG for both TE and TM modes.

As the band edges are shifting with temperature, it is essential to know the change in bandgap with temperature. For this purpose, the bandgap of the PCW is calculated in the temperature ranges 10 -100 K and 300 - 400 K. Even though the bandgap is changing with temperature, however, this change can be ignored since the magnitude of change is very small (of the order 10^{-5}). Figure 5 shows the variation in PBG with temperature and corresponding wavelength at the band edge (band 7). It can be observed that the bands are shifting at nearly same rate and the change in PBG is very minute, and hence it can be taken as a constant for any application.

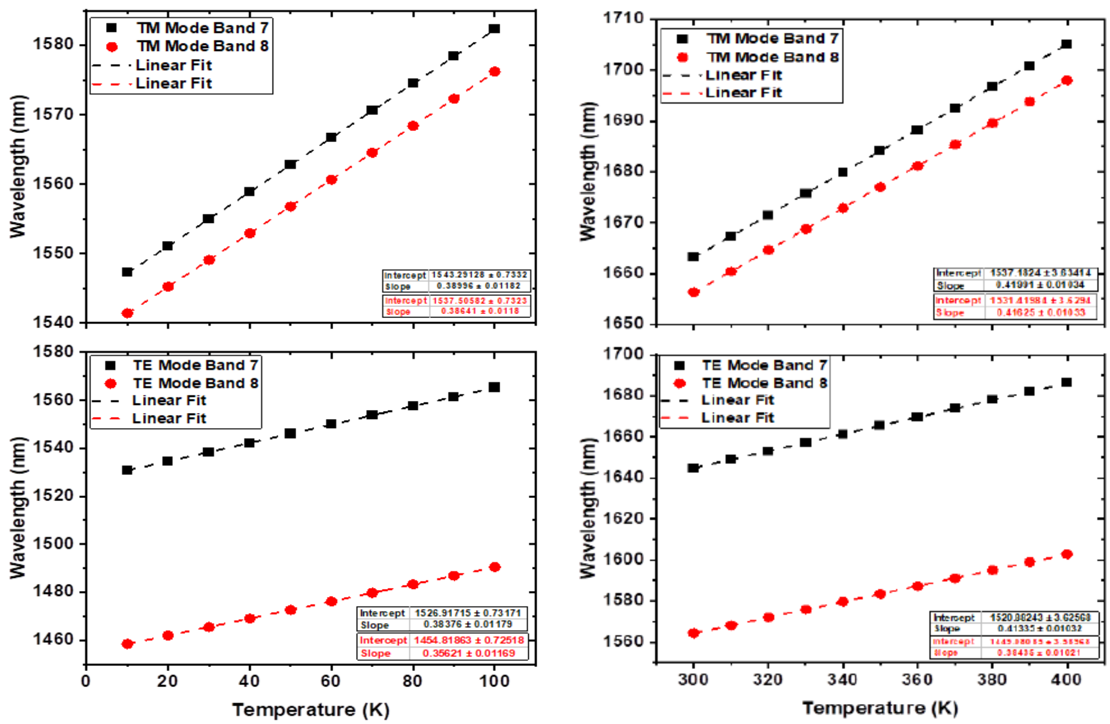

Fig 4. Change in band edge with change in temperature. (a) at lower temperature (b) at higher temperatures.

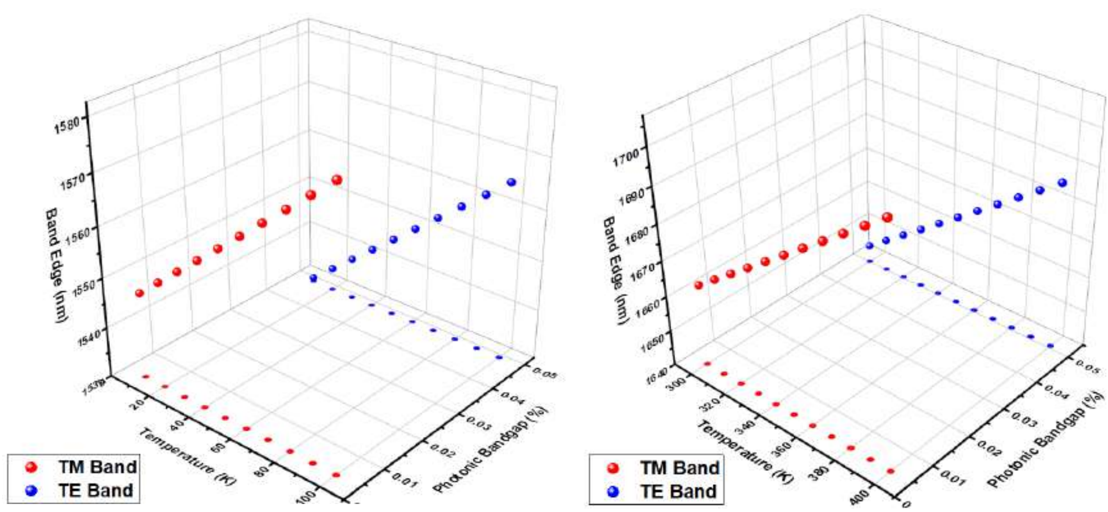

Fig 5. Change in PBG with temperature and corresponding band edge.

4 Conclusions

In conclusion, we designed a PCW with hexagonal lattice. Using thermo-optic effect, the RI of the slab is calculated and used in the simulations. The eigen frequencies and the corresponding eigen wavelengths were calculated for the temperature ranges 10 - 100 K and 300- 400 K. Complete PBG is observed between band 7 and band 8 for both TE and TM modes. The change in band edges with temperature is noticed. A sensitivity of 0.3562 – 0.4199 nm/K is observed. However, the slow heating and cooling rates of the PCW is a restriction on the usage of this structure for real-time applications. By conquering this, the proposed structure may find applications as temperature sensor, wavelength filter and optical trip switch.

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