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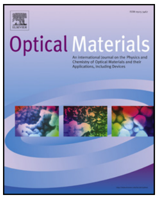

Nano-electric field sensor based on Two Dimensional Photonic Crystal resonator

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ABSTRACT

In this paper, hybrid Silicon-Barium Titanate (Si-BTO) based Two Dimensional Photonic Crystal (2DPC) platform is proposed for electric field sensing based on the effective refractive index modulation of electro-optic material. The nano-sensing platform is composed of the PC based resonator and inline quasi-waveguides in a 2D triangular lattice with circular rods that are arranged in the air medium. The BTO based nano-cavity resonator is playing a very important role in sensing the different electric field over a wide wavelength range. The operating wavelength range of the proposed sensor is investigated via Photonic Band Gap (PBG) which is obtained by the Plane Wave Expansion (PWE) method. The transmission efficiency, quality factor, electric field sensitivity and change in refractive index are analyzed by using Finite Difference Time Domain method (FDTD). The simulation results reveal that the resonant wavelength of the electric field sensor is linearly shifted to the higher wavelength region while increasing the electric field from 0 kV/mm to 25 kV/mm. The proposed sensing platform provides high transmission efficiency and very high refractive index sensitivity with an ultra-compact size. Hence, it is highly suitable for nano-chip based sensing applications.

1. Introduction

In recent years, ultra-compact photonic sensors are extremely attractive and excellent candidates for the optical community, and also it can meet the current demands such as lightweight, low power, ultra-compact size, high-precision and fast response for on-demand real-time applications [1]. The ultra-small electric field sensor is very important for voltage balancing, microwave detection, shielding of electromagnetic radiation, electromagnetic interference prevention, electric industry, detection of charges, radio-frequency reception, and so on [2,3]. Also, electric field sensors are attracted much attention due to their numerous advantages such as safety and remote measurement, intrinsically resistant to electromagnetic interference and rapid response speed [4]. In the literature, high sensitive, low power, highly accurate and ultra-compact photonic sensing platform has developed to detect the electric field for a wide range of application [5]. However, the optical losses are increased while reducing the size of the devices [6]. Alternatively, Photonic Crystals (PC) based devices are effectively utilized to reduce the device size to a nanoscale range with the ultra-low optical loss, and it provides strong photon confinement within the resonator [6].

PC is a kind of artificial nanostructure which is created by periodically arranging the two different materials with different refractive index in a single substrate. The peculiar property of PC is Photonic Band Gap (PBG), which make it suitable for controlling and guiding the light signal at the scale of optical frequency [7]. The light signal in the PBG range is forbidden from propagating inside the structure. However, it can be allowed only by introducing the defects in the periodic PC structure. Fundamentally, the 2DPC platform is an excellent candidate for the optical device due to the simple structure, small size, perfect PBG calculation, strong light confinement and easy to integrate with optical integrated circuits [7]. Over the last two decade, 2DPC platform utilizes to design the various photonic devices such as logic gates [8], filters [9], demultiplexers [10], sensors [11–27] etc.

During the last decade, Si-based PC is a most promising platform for optical sensing applications. However, Si is insensitive to the external electric field and not suitable for electric field sensing because it has very low linear electro-optic coefficients due to their centrosymmetric crystalline structure [28]. Therefore, non-centrosymmetric crystalline structure based high-performance electro-optic material is integrated with Si to enhance the electro field sensitivity. Recent years, hybrid Si-$LiNbO_3$ based PC material is widely used for electric field sensor [29]. However, the $LiNbO_3$ electro-optic coefficients value (r_{33} = 30 pm/V) only 20 times larger than Si and its integration very difficult with Si

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chip [30]. As an alternative material, the nonlinear electro-optic material of Liquid Crystal (LC) and polymer (r_{33} = 150 pm/V) infiltrated into the Si hole is employed to enhance the electric field and voltage sensitivity, respectively [26,27]. However, inserting LC and polymer in the Si hole is very difficult, and the LC extremely produces the slow optical response and it not suitable for photonic integration [31,32].

The challenges above are mitigated using BTO which has very high electro-optic coefficients (r_{42} = 1640 pm/V) [33]. The integration of BTO with Si is very easy compared to other electric-optic material. Also, it produces high-speed responses and consumes less power owing to the use of electric field [34]. The refractive index difference between Si (n = 3.5) and BTO (n = 2.4) is very high, as a result, the light signal is strongly interacted within the photonic device and reduces their optical losses [35]. Hence, BTO is the excellent candidate and tremendously promising platform for PC based nano-optical devices.

In the literature, 2DPC based BTO platform is used to develop very few photonic devices. However, this platform is not utilized for electric field sensing application. Best of our knowledge, 2DPC based hybrid Si-BTO platform is first time proposed to sense the electric field with a good quality factor, high normalized transmission efficiency and high sensitivity with very low detection limit. The 2D-PWE and 2D-FDTD methods theoretically investigate the electric field sensor functional characteristics.

The rest of the paper is structured as follows. The electric field sensing principle discussed in Section 2. The PWE method is used to describe the PBG and structural parameters in Section 3. The photonic crystal resonator based sensor design focuses on Section 4. The functional characteristics evaluation discussed in Section 5. The electric field effect analysis and its sensing parameters optimization discussed in Section 6. At last, Section 7 concludes the paper.

2. Sensing principle

The working principle of electric field sensor is based on the electro-optic effect which means that the electric field is applied to change the refractive index of the electro-optic material (BTO). As a result, the resonant wavelength of the nanosensor will be shifted into the higher wavelength. The relationship between the refractive index of BTO and the electric field is expressed as [36].

$$n = n_0 + \frac{r_{eo} n_0^3}{2} E \tag{1}$$

$$E = V/L \tag{2}$$

where n_0 is the refractive index of BTO (2.289) at zero electric fields (0 kV/mm), r_{eo} is the electro-optic coefficient of BTO which is equal to 600 pm/V at 1550 nm wavelength [37]. L is the distance between two electrodes, and it is set to be 2 μm [36], V is the applied voltage, which should be below the breakdown voltage which is equal to 60 V for BTO [38] and E refers to the electric field. From equation (1) it is observed that for every 1 kV/mm electric field, the refractive index of BTO is increased by 0.003597.

3. Photonic band gap structure

Generally, in 2DPCs, the sensor can be realized by the square lattice or triangular lattice. The triangular lattice have the large bandgap, high filling factor, and less sensitive to structural parameters variation compared to the square lattice. Furthermore, a triangular lattice acts as a good platform for photonic integrated circuits and easily integrated with other nano-optical devices [39,40]. Also, the lattice may be in the form of dielectric rod type or air hole type (dielectric slab). The dielectric rods in air medium is preferred compared to the dielectric slab with hole type PCs due to their low optical losses, easy fabrication and defects based structure effectively produce single mode output [41].

The proposed electric field sensor design is based on 2DPC with the triangular lattice of circular rods arranged in the air background. The periodic PC structure is composed of 27 × 21 circular rods arranged in X and Z directions, respectively. The Si refractive index is 3.5, the radius of the circular rod is 130 nm, and the lattice constant is selected to be 630 nm.

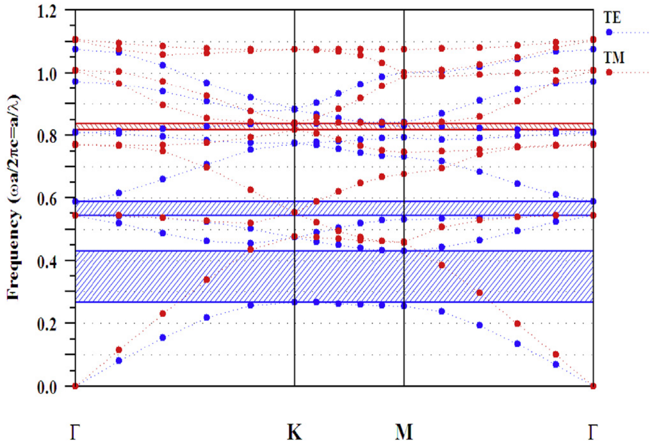

Fig. 1. Band diagram of a 27 × 21 perfect photonic crystal structure for a triangular lattice of silicon rods in air medium for TE and TM mode at a = 630 nm and r = 130 nm. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

The proposed nano-electric field sensor TE and TM Photonic Band Gaps (PBG) are obtained by the Plane Wave Expansion (PWE)method using the aforementioned structural parameters. The triangular lattice of circular silicon rods in air platform-based perfect photonic crystal structure band diagram as shown in Fig. 1. From the Fig. 1, it is observed that the proposed nanostructure have two PBGs for TE polarization(blue color) and one PBG for TM polarization (red color). The first TE PBG (large bandgap)is accounted for electric field sensor design as its wavelength range covers low loss telecommunication wavelength, i.e.,1351.5 nm–2203.1 nm.

The proposed nanosensor structural parameters are accurately optimized by using gap map diagram as shown in Fig. 2(a)–(c).Fig. 2(a) shows the impact of PBG range with respect to the lattice constant. Fig. 2(a), it is observed that the bandgap frequency is shifted to the higher values while increasing the lattice constant. The optimum value of the lattice constant is selected as 630 nm, and it is highlighted by green color over the first TE PBG region.

The impact of PBG range while varying radius of the rod is shown in Fig. 2(b), by increasing the radius of the rod, the PBG frequency is shifted to the lower values. From this analysis, the radius of the rod as 130 nm is accounted for sensor design and it is highlighted by green color over the first TE PBG region. The refractive index of circular rods are silicon (n = 3.5), and the background index is air (n = 1). Hence, the refractive index difference between silicon and air is termed as delta (Δ = 2.5). The delta value is represented by green color over the first TE PBG region, and its wavelength range lies between 1351.5 nm and 2203.1 nm. Fig. 2 (c), it is observed that the bandgap frequency is shifted to the lower values while increasing the delta.

4. Photonic crystal resonator

The Si-BTO coupled photonic crystal resonator based nano-electric field sensor layout structure is shown in Fig. 3 (a). The electric field sensing platform is composed of two inline quasi waveguides in the horizontal direction, and the BTO based PC resonator located between them. The inline quasi-waveguides are formed by line defect introduce to remove the Si rods in the input side and output side. The BTO based PC resonator is created by seven Si rods are (red color) removed to insert the three BTO rods (blue color) with a radius (r_b) of 300 nm and