Design and analysis of a photonic crystal platform on silicon-on-insulator substrate for refractive index based sensing

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Abstract: Two-dimensional photonic crystals having hexagonal lattice with circular holes on silicon-on-insulator substrate is proposed. Effect of lattice constant and hole diameter on photonic bandgap are studied and optimized for visible region. The structure shows a sensitivity of 104 nm/RIU in the refractive index range of 1.2 to 1.4.

OCIS codes: (160.5298) Photonic crystals; (160.5293) Photonic bandgap materials.

1. Introduction

The ability to precisely control the properties of light using photonic crystal (PhC) structure leads to tremendous research interest in various fields such assolar cell, LASER, biosensors[1] etc. Among them, extensive efforts have been made by the researchers in PhC platform for label-free biosensing due to their light confinement property, compactness and sensing potential [2]. Holes etched to form the PhC structure in a high dielectric material can be infiltrated with analytes, thereby change the refractive index (RI) of the holes and thus alter the optical properties of PhC structures. The sensing methodology involves the change in output power and the shifts in wavelength. For a particular lattice, the photonic band gap are determined by various parameters, viz. guiding layer thickness, lattice constant, lattice dimension and dispersion properties of dielectric materials [3]. In this work, we propose a PhC structure based on circular air holes optimized for RI sensing applications using three-dimensional finite difference time domain (3-D FDTD) simulations. The device is considered in a silicon-on-insulator (SOI) substrate consisting of a hexagonal array of holes etched in its silicon device layer to form a PhC structure. The effect of lattice constant and hole diameter on the photonic bandgap using plane wave expansion (PWE) and finite-difference time-domain (FDTD) method are also studied.

2. Theory, principle and model

PhC consist of a periodic arrangement of materials having different dielectric constants. The propagation of electromagnetic waves can be tailored using photonic crystal due to its unique photonic band. The 2-D PhC sensor is considered on a SOI substrate with a Si guiding layer thickness of 220 nm and 1500 nm thick buried oxide layer. The device layer has a hexagonal array of holes with diameter d=120 nm (=0.6a), etch depth of 220 nm on the silicon guiding layer and arranged periodically with a lattice constant, a=200 nm. PWE method is used to calculate the bandgap of the photonic crystal having dielectric constant function $\varepsilon_r(\vec{r})$. Bloch theorem is used to expand the H field in plane wavesgiven by $H(\vec{r}) = \sum_{\vec{G}} \sum_{\lambda=1,2} h_{G\lambda}\hat{e}_\lambda e^{i(\vec{k}+\vec{G})\cdot\vec{r}}$.

The dielectric constant is expressed as $\varepsilon_r(\vec{r}), {}^{1}/{}_{\varepsilon_r(\vec{r})} = \sum \varepsilon_r^{-1}(\vec{G}) e^{i\vec{G}\cdot\vec{r}}$, where $\vec{k}$ is a wave vector in the Brillouin zone of the lattice, $\vec{G}$ is the reciprocal lattice vector, and $\hat{e}_1, \hat{e}_2$ are unit vector orthogonal to $\vec{k}+\vec{G}$ caused by the transverse nature of $\vec{H}$. Substituting $H(\vec{r})$ and $\varepsilon_r(\vec{r})$ in the master equation we obtain,

$$\sum_{G'} \left|\vec{k}+\vec{G}\right|\left|\vec{k}+\vec{G}\right| \varepsilon_r^{-1}\left(\vec{G}-\vec{G}'\right)\begin{pmatrix} \hat{e}_2\cdot\hat{e}_2' & -\hat{e}_2\cdot\hat{e}_1' \\ -\hat{e}_1\cdot\hat{e}_2' & \hat{e}_1\cdot\hat{e}_1' \end{pmatrix} h_{G'\lambda} = \left(\frac{\omega}{c}\right)^2 h_{G\lambda} \tag{1}$$

where c is the speed of light. The above equation is solved for different values of wave vector $\vec{k}$ to obtain a series of eigen-frequencies ω , which determines the band structure of the photonic crystal.

3. Results and Discussion

The photonic band diagram for SOI based PhC structure with lattice constant a=*200* nm and air hole-diameter *0.6a* is shown in Fig. 1(a). TE photonic band is observed in the visible wavelength ranging from 591–697 nm. The effect of lattice constant on photonic band gap is shown in Fig. 1(b) for a hole-diameter of 0.6a. As the lattice constant is increased the wavelength range in which the photonic band gap is formed also increased. It is found that the lattice constant must be of the order ~200 nm to achieve the bandgap in the visible range for the proposed structure. The filling factor of a hexagonal lattice with air hole in PhC structure is given by $\left(\frac{2\pi}{\sqrt{3}}\right)\frac{R^2}{a^2}$. Fig. 2(a) represents the effect of air-hole diameter on the band gap of PhC for a lattice constant of 200 nm. Photonic band gap increases with hole-diameter due to the increase in fill factor. Thus, a visible range SOI based PhC sensor platform is optimized with hexagonal lattice of 200 nm, hole diameter of 0.6a (120 nm) and etching depth of 220 nm in Si guiding layer. The optimization is undertaken using FDTD calculation in guided mode resonance (GMR) with a Gaussian exciter having central wavelength of 550 nm. Reflectance characteristics of the structure in GMR mode are simulated for a range of RI (1.00-1.42), as shown in Fig. 2(b). The device shows an average sensitivity of 104 nm/RIU for RI in the range of 1.2-1.4, as shown in Fig. 2(c).

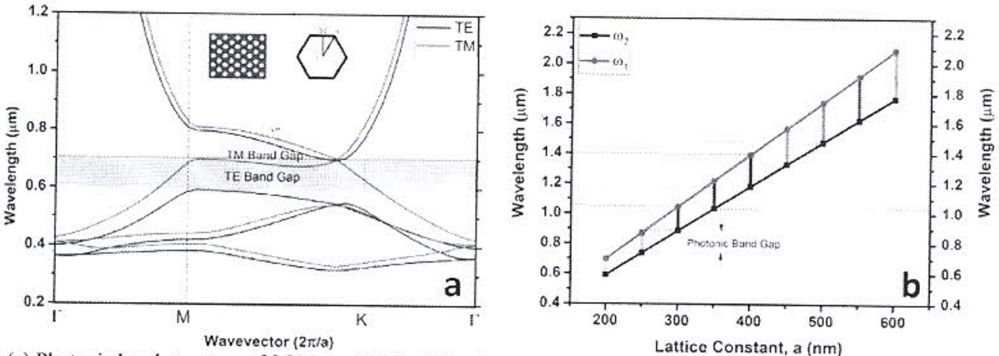

Figure 1: (a) Photonic band structure of SOI based PhC with lattice constant a=200 nm and air hole-diameter 0.6a, (b) Study of photonic bandgap with the variation of lattice constant in SOI based PhC structure.

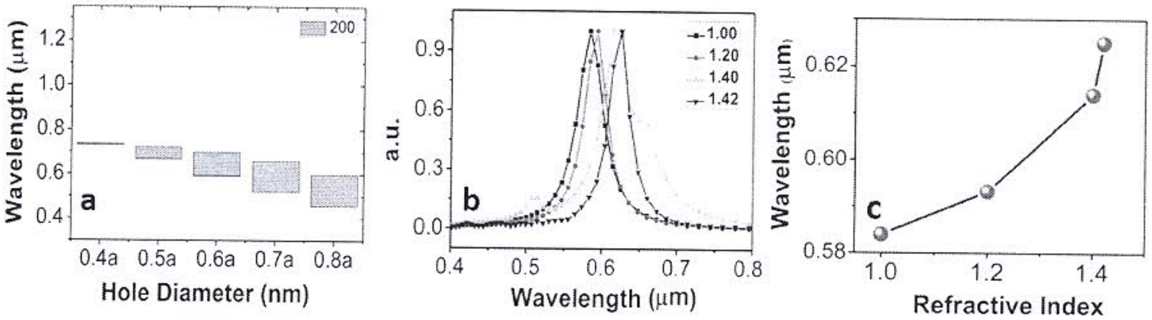

Figure 2: Variation of photonic bandgap as a function of hole-diameter in SOI based PhC structure for lattice constant of (a) 200 nm. (b) Reflectance characteristics and (c) sensitivity for the proposed PhC based optical sensor platform.

4. Conclusion

Design of a SOI-based 2-D PhC structure with hexagonal array of air hole is reported. Effect of lattice constant and hole diameter are studied and analysed to achieve the bandgap and resonance wavelength in the visible region. The optimised structure with a lattice constant of 200 nm and hole-diameter of 120 nm exhibits a sensitivity of 104 nm/RIU in the RI range of 1.2 to1.4. This structure can be fabricated with state-of-art facility of electron-beam lithography or laser interferometry and can be used as a platform device for various sensing applications including healthcare diagnostics.

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5. References

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