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Theoretical study on biosensing characteristics of heterostructure photonic crystal ring resonator

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ABSTRACT

In this paper, we investigate the biosensing characteristics of two-dimensional heterostructure photonic crystals (PCs) ring resonator theoretically by using the finite difference time domain (FDTD). The coupling air holes and inner air holes of ring resonator are treated as coupled sensing area and internal sensing area. When both of the sensing areas are filled with the same biological samples solution, the resonant peak wavelength shift of the ring resonance is different. Both the resonant peak center wavelength and peak intensity are related to the positions of sensing holes. With the same refractive index change of the biological sample, the sensing sensitivity of the coupling sensing area is much higher than that of the inner sensing area. Meanwhile, through the analysis of resonant peak wavelength shift, the refractive index change of the sample filled in the sensor area can be derived, which can be monitored real-time.

1. Introduction

In recent years, food safety, environmental protection, medical diagnosis and other issues are becoming increasingly prominent, which not only puts forward higher requirements on the rapid identification and detection of biological samples, but also provides opportunities of further development for biosensing technology. Label-free, fast, real-time, convenient detection method has become a hot area of engineering research [1–3]. In 2004, Asher et al. from Pittsburgh University have done a lot of research about using colloidal photonic crystal as a carrier for the detection of human physiological parameters, and present a complete concept of photonic crystal biosensor relatively [4]. At the beginning of 2011, the porous silicon PCs that are suitable for optical immunity detecting have been prepared by controlling the experimental conditions. Then the biological immune sensor was prepared as a result of oxidizing the porous silicon, silylation, covalently handling between glutaraldehyde cross-linking and antibody, measuring the fourier transform infrared Raman spectroscopy before and after the antigen antibody reaction by joining spaA antigen, and the detection limit was 1.412×10^2 pg/ml [5]. Currently, real-time monitoring of biological molecules plays a crucial role in biological research, and the biosensors based on photonic crystal that has the high sensitivity characteristics for analysis of the spectra band provide a new way to solve this problem.

PCs are composed of two or more dielectric materials of different dielectric constants periodically arranged in space [6,7]. And there is a huge potential applications prospect because of its photonic band gap and photon localization characteristics etc. So far, the theoretical basis study of PCs has been growing perfection, and the design of photonic crystal devices to achieve specific functions will become the focus of research, such as photonic crystal optical switches [8], photonic crystal fibers [9], photonic crystal filters [10] and so on. In respect of the biosensor, the researchers are attaching great importance to photonic crystal sensor because of its high sensitivity, small volume, easy integration and low cost [11,12]. A micro-ring resonator composed of straight waveguides and point defects can be designed to a biosensing structure, which has a good sensitivity. And the sample information detection can be achieved dynamically by modifying the information of one or more holes of local position [13,14].

Based on the above analysis, in the range of photonic band gap of this paper, we use photonic crystal ring resonator as a biosensor structure.The coupling air holes and inner air holes of ring resonator are treated as coupled sensing area and internal sensing area respectively. When both of the sensing areas were filled with

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0030-4026/

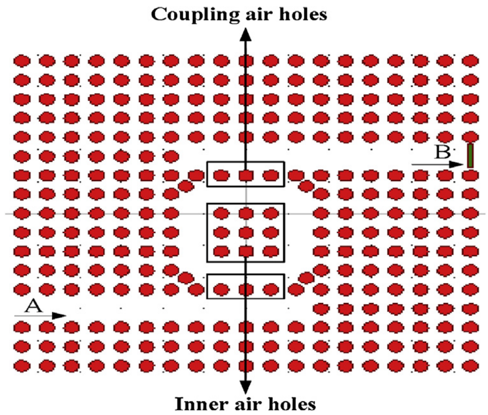

Fig. 1. Layout sketch of the PCs based ring resonator sensor structure.

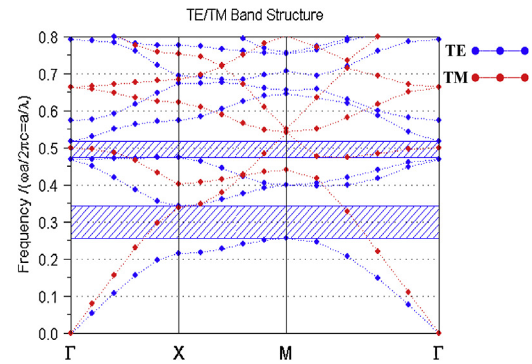

Fig. 2. Band structure of square lattice photonic crystal of TE polarized light and TM polarized light.

the same biological samples solution, the corresponding resonance center wavelength will appear in the transmission spectrum, which illustrates both the resonant peak center wavelength and peak intensity are related to the positions of sensing holes. With the change of biological sample refractive index, the resonance wavelength shift of defect states photonic crystal structure will change accordingly. By analyzing the resonance peak wavelength shift, the refractive index change of the sample filled in the sensing area can be derived, which can be monitored in real time.

2. Theoretical models

The sensing structure based on photonic crystal ring resonator as shown in Fig. 1. The inset of Fig. 1 denotes single crystal silicon as the high refractive index background of photonic crystal, and its refractive index of 3.4, the air hole radius of 0.45a, its refractive index of 1, where a is the lattice constant. We use 19 × 17 air holes distribution model for numerical calculation. Gaussian pulse signal light is launched into the port A, the bottom terminal waveguide is refereed as the bus waveguide which allows the input light from the left side of waveguide to excite the resonant mode of the ring resonator, then the resonant light coupled to the upper terminal waveguide i.e., the port B output resonant wavelength transmission spectrum. When the periodic distribution of the photonic crystal is disrupted, it will form a defect. Usually two kinds of point defects and line defects may constitute a photonic crystal resonant cavity. The ring resonator structure in this paper is made up of point defects and line defects together. The inset of Fig. 1 denotes the four corners of the ring resonator are respectively provided with an air hole (point defects) to reduce the light scattering and improve the transmission efficiency of light. The coupling air holes between the ring resonator and the input/output waveguide as well as the air holes inner the ring resonator will have an impact on mode coupling between the waveguide and cavity. The corresponding resonant peak will appear in the transmission spectrum when the biological sample is filled in the coupling holes and the inner holes.

Plane wave expansion (PWE) is a method which is widely used for photonic crystal modeling since it can yield accurate and reliable results. Here, we summarize the theory very briefly. The electromagnetic field is unfolded in the form of superposition of plane waves within the reciprocal lattice vector space, which converts Maxwell's equations into TE polarized light and TM polarized light. The relation between wave vector k and angular frequency ω within the first Brillouin zone can be obtained by solving the equation eigenvalue. The $k-\omega$ relation for periodic structure is called the band structure [15].

2-D PWE methods are employed to estimate the square lattice photonic band gap of TE polarized light and TM polarized light as shown in Fig. 2. The vertical axis represents the normalized frequency $\omega a/2\pi c(a/\lambda)$, the abscissa $\Gamma-K-M-\Gamma$ represents Bloch wave vector of the first Brillouin zone. The band structure has shown that the reduced first wider photonic band gap extends from 0.25641 to 0.34359 for TE polarized light, i.e., electric field is parallel to surface of silicon device layer, and the reduced second photonic band gap extends from 0.47436 to 0.51795. The photonic band gap for TM polarized light that is marked with the red line does not exist. Usually we choose the relatively wider band gap, and the corresponding wavelength range of the band gap is between 1.309 μm and 1.755 μm.

3. Results and discussion

The finite difference time domain (FDTD) method is a numerical method which can be used to solve propagation problem of electromagnetic wave, this article will investigate the biosensing characteristics of two-dimensional PCs ring resonator theoretically by using FDTD. The perfectly matched boundary layers (PMLs) are surrounded the whole structure as absorbing boundary condition, and the number of PMLs is set to be 15. The FDTD mesh size used in this paper is: $\Delta x = \Delta y = a/20$. In order to make the solution of differential equations discretized is convergence and stability, the time step Δt must satisfy with Courant stability condition that is $\Delta t \le 1/c\sqrt{1/(\Delta x)^2 + 1/(\Delta y)^2}$, where c is speed of light in free space. Gaussian pulsed light signal is launched into the port A, the output signal is recorded by a time monitor at the output port. The coupling air holes and inner air holes of ring resonator indicated in Fig. 1 are treated as coupled sensing area and internal sensing area respectively, then the output spectrum is obtained by applying the Fast-Fourier Transform to the temporal signal recorded by the time monitor.

3.1. Detection of sample when coupling air holes position as a sensing area

We investigate the coupling air holes as the sensing area because they are located between input/output waveguide and the ring resonator, which has high sensitivity. Assume that the refractive index of the samples of the sensing area changes from 1.33 to 1.5, and the resonant center wavelength of aqueous solution is treated as the reference standard. So initially we consider all surface of coupling sensing area is covered by water, and the derived resonance peak wavelength is shown as the blue peak in Fig. 3, the resonant peak center wavelength of aqueous solution reveals at 1.4375 μm with the normalized transmission of 90%. Furthermore, the coupling sensing holes are fully occupied with different refractive index of samples. The variation of refractive index of samples in such sensing holes is considered as 0.2.