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Radius vertical graded nanoscale interlaced-coupled photonic crystal sensors array

Pan Zhang, Huiping Tian*, Daquan Yang, Qi Liu, Jian Zhou, Lijun Huang, Yuefeng Ji

The State Key Laboratory of Information Photonics and Optical Communications, School of Information and Telecommunication Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China

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ABSTRACT

A radius vertical graded photonic crystal sensors array based on a monolithic substrate is proposed, which is potentially to be used as label-free detection in aqueous environments. The sensors array device consists of five resonant cavities including three H1 cavities and two L2 cavities which are interlaced-coupled to a radius vertical graded single photonic crystal line defect waveguide (W1). Each resonator has a different resonant wavelength dip which can shift independently with crosstalk lower than -13 dB in response to the refractive index change of air holes around every cavity. With three-dimensional finite-difference time-domain (3D-FDTD) method, simulation results demonstrate that the quality factors of microcavities are over 10^4. Besides, the refractive index sensitivity is 100 nm/RIU with the detection limit approximately of 5.63×10^{-4}. Meanwhile, the radius vertical graded photonic crystal with more interlaced cavities is more suited to ultracompact optical monolithic integration.

1. Introduction

Photonic crystal (PhC) sensor is widely used for lab-on-a-chip applications due to its advantages including ultracompact size, high sensitivity and more suitable for monolithic integration. During the last decades, many structures have been proposed to realize photonic crystal sensors, such as microcavities [1,2], slot waveguides [3,4], resonant rings and disks [5], heterostructures [6,7], and so on. These numerous different architectures have been developed in nearly all sensing detection cases, like stress sensing, refractive index sensing, temperature sensing, and biochemical sensing [8–11]. The sensing detection mechanism relies on the shift of the resonant wavelength peak due to the change in refractive index.

With the extensive research about photonic crystal sensors, photonic crystal sensor arrays have attracted considerable interest for subminiature and integrated sensing. Sensor arrays could combine the high quality factor, high sensitivity with the ability to multiplex multiple detection sites. Since Mandal et al. firstly proposed the nanoscale optofluidic sensor arrays based on silicon waveguide with 1D (one dimensional) photonic crystal microcavity [12], many researchers have focused on the study of sensor arrays. Examples of such research include that of Gylfason who demonstrated on-chip temperature compensation in an integrated slot-waveguide ring resonator refractive index sensor array [13], Iqbal et al. who designed label-free biosensor arrays based on silicon ring resonators and high-speed optical scanning instrumentation [14], and Pal et al. who proposed a multiple nanocavity coupled device for error-corrected optical biosensing [15]. All these devices are applied as sensor arrays for accurately sensing detections but not suitable for compact optical integration.

The graded photonic crystal is an interesting topic in recent years. Works have mainly focused on the electromagnetic waves which propagate and transform along the graded structure. Due to its ability of efficiently controlling the light propagation, the graded photonic crystal has been successfully applied as light bending and demultiplexer [16–18]. What's more, since the electromagnetic waves in the graded structure have different light properties, it has also been used as lens in practical applications [19,20]. According to the advantages of radius-graded structure, if we combine it with cavity multiplex as photonic crystal sensors array, the sensing scale could be smaller than that proposed in [12,15].

In a previous work [21], we have proposed a photonic crystal sensors array with radius grading along waveguide direction, which consisted of four resonant cavities. In this paper, we describe a new photonic crystal sensors array based on the radius vertical graded structure. This design contains five resonant cavities (three H1 cavities and two L2 cavities) interlaced-coupled along W1 waveguide, which makes it more suitable to ultracompact optical monolithic integration. FDTD (finite difference

* Correspondence to: Beijing University of Posts and Telecommunications, P.O. BOX 90, #10 Xitucheng, Road Haidian District, Beijing 100876, China.
E-mail address: hptian@bupt.edu.cn (H. Tian).

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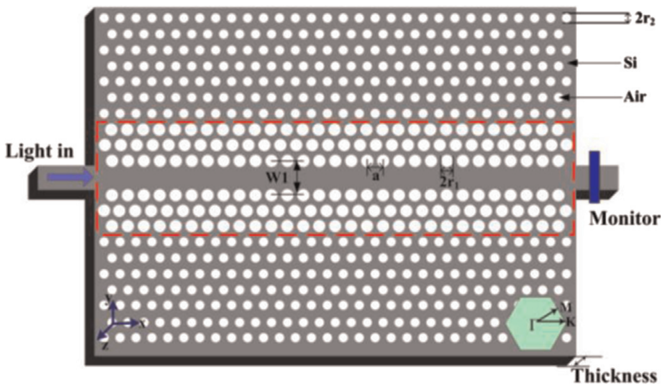

Fig. 1. 3D illustration of the radius vertical graded photonic crystal with a line defect waveguide, where $a=416$ nm, $T=0.58a$, $r_1=0.32a$, and $r_2=0.28a$. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

detection. In addition, the resonant wavelength shifts linearly with refractive index change, and the sensitivity of the sensor array is 100 nm/RIU. The detection limit of refractive index changes (DL) determined by resonant wavelength, sensitivity and quality factor is about 5.63×10^{-4}. The footprint of our design is only $12.48\times7.20\ \mu m^2$ which is much smaller than $60\times60\ \mu m^2$ proposed in [22]. It is essential for photonic crystal sensors array application for the compact optical integrated circuit in the future.

2. Design of the photonic crystal sensors array based on radius-graded structure

2.1. Side-coupled resonant cavity design

Fig. 1 shows a 3D illustration of our radius vertical graded photonic crystal waveguide structure design which is based on

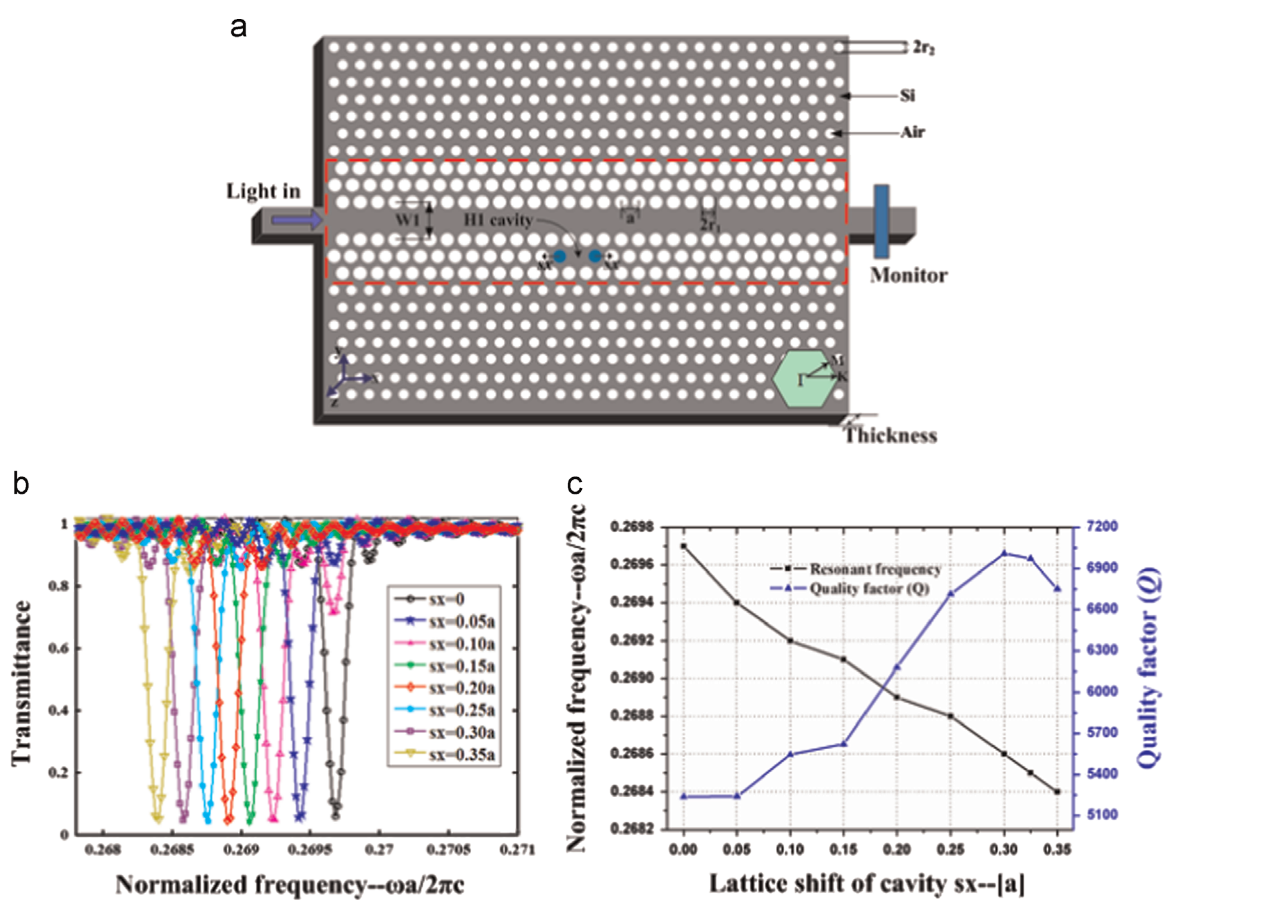

Fig. 2. (a) Schematic diagram of the radius vertical graded PhC with H1 cavity; (b) transmission spectra of TE-like polarized light in resonant cavity with different shifts ranging from $sx=0$ to $sx=0.35a$; and (c) results of FDTD calculations showing the resonant frequencies and quality factors on different sx.

time domain) method is a numerical analysis method that directly uses Maxwell's equations to simulate the electromagnetic field. FDTD has a wide range of applications. One can use FDTD to simulate performances of various complex electromagnetic structures, including scattering, radiation, transmission, absorption, and so on. With the development of time step, FDTD can directly simulate the transmission of electromagnetic wave and its interaction with the object so that the researchers can get a clear description. Through the 3D-FDTD simulation of our designed structure, we can observe that each cavity has much higher transmittance and Q factor. The dip is down to 0.03 and the Q factor is up to 10^4, which is beneficial for accurately sensing

triangular lattice and hole-array. It is constructed in a silicon slab ($n_{si}=3.48$) by arranging a triangular lattice of air holes, where the central row of air holes is removed in order to form a line defect waveguide (W1). In this paper, the preliminary analysis of structures has been performed by using the commercial FDTD software RSoft to calculate their photonic band structure and transmission spectra [2]. For improving the accuracy in the simulation, FDTD analysis of photonic crystal structure is carried out with a grid size of $a/100$ and time step of $0.025a/c$, where a is the lattice constant. All the simulations are carried out with the same grid size and time step for future comparable results. The boundary conditions at the spatial edges of the computational domain must be carefully