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Photonic crystal stress sensor with high sensitivity in double directions based on shoulder-coupled aslant nanocavity

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ABSTRACT

In this paper, we demonstrate a photonic crystal (PhC) stress sensor with high sensitivity in two orthogonal directions. The stress sensor consists of an aslant lattice-shifted resonant cavity shoulder-coupled to two terminated Γ–K waveguides. The linear relationship between the shifts of resonant wavelength and applied stress in double directions is calculated with the finite element method (FEM) and finite difference time domain (FDTD) simulations. With the simulations, we demonstrate that the stress sensitivity of 7.5 nm/μN in horizontal direction and 10 nm/μN in vertical direction is achieved, respectively, and a stress detection limit is approximately of 58 nN and 44 nN in horizontal and vertical direction for this device, respectively.

1. Introduction

In the past few decades, photonic crystal (PhC) has been attracting an increasing interest since Yablonovitch and John proposed in 1987, respectively [1,2]. PhC has wide photonic bandgap (PBG) and photon confinement ability; these optical characteristics have attracted more and more interest in the manufacturing optical devices. Lately, due to the robust characteristics such as small size, high sensitivity, accurate limit of detection and can be easily integrated, a variety of sensing applications have been investigated and developed by employing PhC structures. Sensors based on PhC have been designed for temperature sensing, biochemical sensing, humidity sensing and so on, as result of they are sensitive to tiny perturbation of the refractive index that corresponds to the surrounding temperature [3], the bounding of biochemical molecules [4–6], or humidity around [7]. Most of such PhC structures consist of relatively low-loss waveguides [8] and nanocavities with high quality factor [6,9], which are favorable for superminiature integrated sensor applications.

Besides, mechanical sensing by using PhC structures has also been studied so far [10–15]. For example, Yang et al. carried out a microdisplacement sensor based on slot PhC structure with high Q factor cavity that utilizes the intensity of transmittance spectra as a token of the displacement [10], Lu et al. proposed a stress sensor based on the changes of optical properties caused by the variation of double-layered photonic crystal microcavity [11] and Lee et al. proposed stress sensors with high sensitivity based on PhC which measure changes in the resonant frequency in transmittance spectra when forces were applied on the cantilever [12–14]. In addition, Winger et al. presented a nanocavity with electromechanical and optomechanical characteristics, which combined with an electrical circuit with a high quality factor PhC nanocavity to realize electrokinetic sensor [15]. However, in these studies, the generated stress on these measurements were just taken along in one direction [12,13], stress sensors operated in multiplex directions were not studied.

In our paper, we demonstrate a stress sensor with a high quality factor aslant nanocavity that makes it possible to achieve high sensitivity in both the horizontal and vertical direction. The cavity we designed is 60° from Γ–K direction so that the applied stress in both directions generated almost the same geometry variations on the cavity. With this stress sensor fixed on the base, we can detect the stress from two orthogonal directions which is important in multidirectional and reusable stress sensing. In order to leak the light inside the cavity onto the output waveguide for detecting the resonant wavelength in transmittance spectra, the cavity is shoulder-coupled [16] by two symmetrical W1 waveguides to acquire a stronger coupling strength. Firstly, with the FEM simulation, we obtain the variations of air holes caused by the applied stress. Then the structure variations lead to the shift of the resonant

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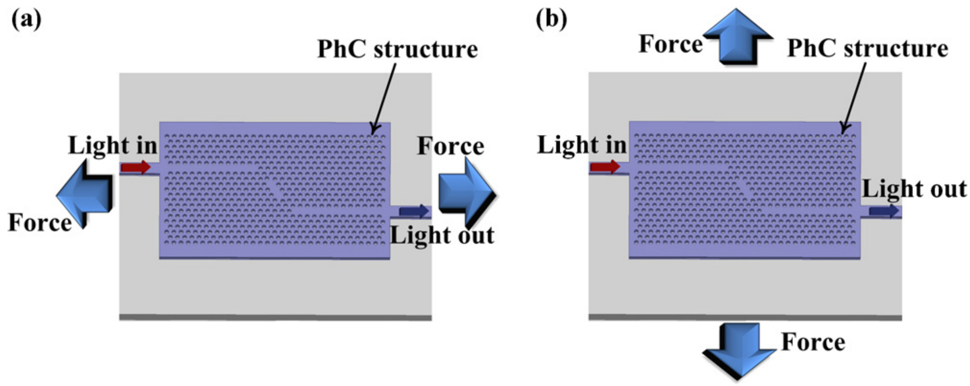

Fig. 1. Schematic of the stress sensor design under stress in horizontal direction (a) and vertical direction (b).

wavelength, the shift of output resonant peak was calculated by 3D FDTD simulation. Ultimately, by utilizing FEM and 3D FDTD simulations together, the sensitivity of 7.5 nm/μN in horizontal direction and 10 nm/μN in vertical direction is obtained, respectively, and a stress detection limit is approximately of 58 nN and 44 nN in horizontal and vertical direction for this device.

2. Stress sensor design principle

2.1. Stress sensing principle

Fig. 1 presents a schematic of the stress sensor design based on a piece of Si PhC structure. There are two waveguides and one aslant cavity created on the structure by removing or shifting the air holes. The geometries and positions of the air holes were modified by applying mechanical force on the structure. The stress sensing can be realized from the measurement of change in the optical property.

There are two ways to detect the stress by measuring the change of optical properties. The first one is paying attention to measuring the variation of intensity in transmittance spectra. The other one is by observing the shift of specific wavelength. However, we choose the latter one in this case because many factors may impact the intensity and cause errors. Here we choose the resonant wavelength of the aslant cavity as the candidate and observe its shift to deduce the applied force. The direction of stress can be differentiated by detecting the resonant wavelength has a red shift or a blue shift. And the value of stress can be known by measuring the displacement of the resonant wavelength. By utilizing FEM and 3D FDTD simulations together, we could estimate the force by measuring the shift of resonant wavelength and calculate the sensitivity (S, defined as resonant wavelength shift in nanometer per stain variation in micro Newton unit, that is, nm/μN) of this stress sensing structure. Eq. (1) is defined to illustrate this relationship:

$$S = \frac{\Delta\lambda}{\Delta F} \tag{1}$$

where $\Delta\lambda/\Delta F$ represents the resonant wavelength shift caused by the specific applied force. With the high Q factor cavity we can achieve large $\Delta\lambda/\Delta F$, that is, larger shift of resonant wavelength on the condition that fixed stress has been set. Then the stress detect limit can be defined (L, in nano Newton unit) with the line-width of the resonant peak, which is equal to the quality factor. Thus Eq. (1) can be modified to:

$$L = \frac{\Delta F}{\Delta\lambda} \times \frac{\lambda}{Q} = \frac{\lambda}{SQ} \tag{2}$$

where, λ, Q, and λ/Q represent the resonant wavelength of the cavity, the quality factor, and the line-width of the resonant peak, respectively. Consequently, the detect limit L is influenced by two significant parameters: S and Q. When the sensitivity is fixed, we can achieve small L with this high quality aslant cavity in horizontal direction (Fig. 1(a)) and vertical direction (Fig. 1(b)). The nonlinear effect such as Kerr effect can also change the refractive index of Si. However, according to Ref. [17], when the injected light power is not too high, the variation of refractive index is ultra-small. When the input power was 60 μW, the refractive index changed 0.5×10^{-4} and we found that the resonant wavelength shifted only 6.239×10^{-4} nm. It is really small to affect the sensing property.

2.2. PhC structure design

In the past few decades, PhC cavity structures have been drawing much attention for its small mode volume and ability to strongly confine light. Many studies have focused on putting forward various cavities [18,19] and optimizing the cavities geometry [20,21]. But these cavities are almost constructed parallel to the direction of light propagation so that insensitive to the stress applied in other directions except the direction along the cavity. In order to obtain robust sensing performance in both directions, we present an aslant cavity to achieve the goal.

The detail of the PhC structure has been shown in Fig. 2, as the PhC structure is the key component of the stress sensor and play a crucial role in the stress sensing sensitivity. Particularly, the aslant cavity is the core of the PhC structure because the performance of the cavity influences the property of the whole sensor. Triangular lattice design are structured in a silicon slab (n_{si} = 3.48) with air holes, where the two air holes (in the direction 60° from Γ–K direction) are shifted from the original lattice positions and the three air holes between them are filled to construct an aslant cavity. In this

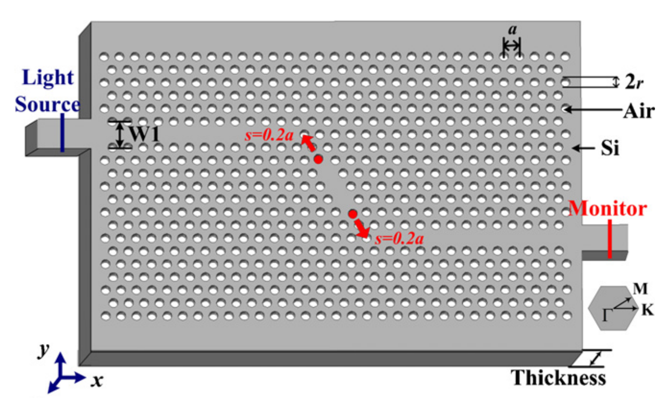

Fig. 2. 3D schematic of the PhC structure, where lattice constant a = 385 nm, diameter of air holes d = 0.6a, thickness t = 0.56a, shift of holes s = 0.2a, refractive index of Si n_{si} = 3.48.