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Nanomechanical three dimensional force photonic crystal sensor using shoulder-coupled resonant cavity with an inserted pillar

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ABSTRACT

A nanomechanical three-dimensional force photonic crystal (PhC) sensor is proposed in this paper by using a shoulder-coupled aslant resonant nanocavity with a single inserted Si pillar and the sensing characteristics are theoretically analyzed and demonstrated. This sensor can be used to detect nanomechanical force in three orthogonal directions independently by measuring the shift of resonant wavelength. The aslant resonant cavity with high quality factor of 7800 ensures high force sensing sensitivity in every dimension as the sensitivity can be enhanced by optimizing the cavity. The shoulder-coupled PhC structure and mobile Si pillar ensure the sensor can detect force from every direction. By applying finite element method (FEM) and finite difference time domain (FDTD) simulations, sensing sensitivity of 8.2, 12.5 and 10.9 nm/μN have been achieved in three dimensions and limitation of the smallest detectable force is 24, 16 and 18 nN in three dimensions, respectively.

1. Introduction

A nanomechanical sensor is the device to detect nanomechanical variations such as deformation, force, acceleration, displacement and so on. It has been broadly used in microelectromechanical system (MEMS) as sensing is the key part in the whole process when forming MEMS. Most of the nanomechanical sensors researched in recent decades were based on fibers [1–3] or carbide [4,5]. However, a huge obstacle is impassable when integrating fibers, carbide with common silicon devices. Sensors utilizing photonic crystal (PhC) based on silicon can easily solve this problem because their convenience to be integrated with silicon devices and small scale size.

PhC has been attracting an increasing interest since Yablonovitch and John proposed in 1987, respectively [6,7]. In the past few years, different kinds of PhC sensors used in biosensing [8–10], gas sensing [11,12] and temperature sensing [13] have been come up. Optical nanomechanical sensors [14–19] based on PhC have been also researched for its ultra-small size, high sensitivity and ease of integration with Si devices. For example, Lee et al. presented the design and optimization of a nanomechanical sensor by using U-shaped silicon PC waveguide to detect micro-strain [14], Yang et al. demonstrated a novel nanoscale photonic crystal pressure sensor with PhC waveguides and piston-type microcavity [15], Li et al. investigated a nano-scale force and pressure sensor by integrated with three nano-ring resonators together [16], Tian et al. demonstrated the relationship between out-of-plane nanomechanical deformations and the tuning of double-coupled one-dimensional photonic crystal cavities [17], 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 [18] and Yang et al. proposed a method to detect nano-stress in two dimensions within a single PhC structure [19]. Most of the nanomechanical sensors mentioned above provide ultra high sensitivity [14,19] and they are very small in size [15,16] so that they can be used in MEMS. However, the sensors can only detect nanomechanical variation in one dimension, and they are difficult to be integrated to realize sensing of the nanomechanical variation in three dimensions. The ability to sense nanomechanical variation in more than one dimension is requisite and it would be best for designing a single structure to realize this function.

In this paper, we propose a three dimensional photonic crystal nanomechanical sensor based on shoulder-coupled resonant nanocavity with an inserted pillar which can be used to detect the nanomechanical variation in three dimensions with high

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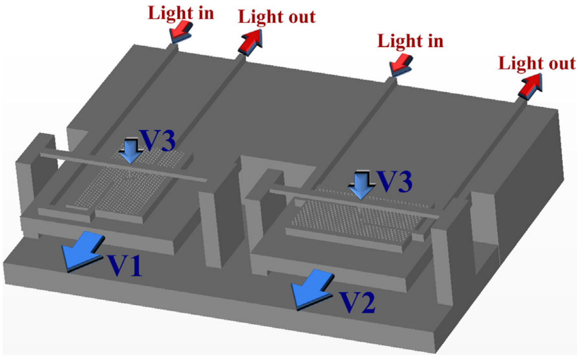

Fig. 1. Schematic of the nanomechanical three dimensional force sensor design. Force is applied in horizontal direction (V1), vertical direction (V2) and upright direction (V3), respectively.

sensitivity and the characteristics of the sensor are theoretically analyzed. The structure is formed by a pillar-inserted aslant nanocavity which is shoulder-coupled by two W1 waveguides. Light is injected into the aslant cavity through the input waveguide and the light leaked from the cavity is monitored at the end of the output waveguide. A sharp peak corresponding to the resonant wavelength in the transmittance spectra is used as pointer to detect the nanomechanical variation. As shown in Fig. 1, when the nanomechanical force is applied on the structure from one direction in the plane, the mechanical deformation of the PhC structure caused by the force will shift the resonant wavelength. When the nanomechanical force is applied from the direction perpendicular to the plane, the pillar will be inserted into the tiny air hole in the middle of the cavity and the resonant wavelength will be also shifted because the variation of the cavity affects the resonant wavelength. The value of force can be known through the displacement of the resonant wavelength shift because of the linear relationship between the displacement of shift and the applied mechanical force. In this paper, firstly we will introduce the theory of nanomechanical variation sensing and the design of PhC structure. The optical properties of the cavity and the whole structure will be investigated by the finite difference time domain (FDTD) simulations. Then the mechanical variations caused by force in three dimensions will be investigated by the finite element method (FEM) simulations, respectively. Finally by combining the results of FDTD and FEM simulations together we will discuss the sensing properties of the structure in the every direction, respectively.

2. Theoretical analysis and design principle

2.1. Nanomechanical force sensing principle

When the nanomechanical force is applied on the optical force sensor, the deformations of the sensing structure caused by the force will lead to some variation of the optical properties. And there are two ways to detect the value of force by measuring the variation of transmitted intensity [15,20] or the shift of specific wavelength [16,19,21–23]. We choose to measure the shift of resonant wavelength in our study because the intensity of resonant wavelength varies a little under different value of force in our study and this will arouse inaccuracy in the measurement of nano-force. As shown in Fig. 1, the force from horizontal direction (V1), vertical direction (V2) parallel to the PhC slab plane and upright direction (V3) perpendicular to the PhC slab plane will all cause the variation of the resonant cavity, and the resonant wavelength of the cavity will shift, respectively. By applying FEM and FDTD simulations we can calculate the value of force by measuring the displacement of resonant wavelength.

2.1.1. Force parallel to slab plane

V1 and V2 in Fig. 1 show the nano-force (F) is applied parallel to the plane in two directions and Fig. 2(a) and (b) shows the schematic deformation of the air holes under force of V1 and V2. The point force is applied on the edge of the substrate so that the PhC structure fixed on the substrate can generate geometric variation. The air holes' geometries and positions on the PhC slab are all modified and the resonant wavelength will shift due to the corresponding variation of PhC structure. With FDTD simulations, the shift of resonant wavelength ($\Delta\lambda$) can be obtained. Here, we define the sensitivity (S_a, nm/μN) of this nanomechanical force sensing structure when force is applied parallel to the plane in horizontal or vertical direction as follow:

$$S_a = \frac{\Delta\lambda}{\Delta F} \qquad (1)$$

where $\Delta\lambda/\Delta F$ represents the displacement of resonant wavelength caused by the applied force. In addition, the limit of nano-force detection L_a (nN) when force is applied parallel to the slab plane can be defined as the minimum detectable force variation, however, the force variation is reflected by the shift in the transmission spectrum, that is the minimum spectral resolution of measured light wave, which is decided by the measured optical line-width in spectrum, or equivalently, Q factor. Therefore with the substitution of Eq. (1), L_a is defined as follow:

$$L_a = \frac{\Delta F}{\Delta\lambda} \times \frac{\lambda_c}{Q} = \frac{\lambda_c}{S_a Q} \qquad (2)$$

where, λ_c, Q, and λ_c/Q represent the resonant wavelength, the quality factor of the cavity, and the line-width of the transmission peak, respectively. From Eq. (2), we know that the detectable limit L_a is mainly affected Q. And smaller L_a can be achieved with higher quality factor when the force is applied in horizontal direction and vertical direction in Fig. 1 parallel to the slab plane.

2.1.2. Force perpendicular to the slab plane

V3 in Fig. 1 shows the force perpendicular to the slab plane is applied on the structure and the single pillar is inserted into the air hole in the middle of the cavity under force in upright direction as shown in Fig. 2(c). The point force in V3 direction is applied on the center of the Si strip. Similarity to the force applied parallel to the plane, we can get the sensitivity S_d (nm/μN) of this nanomechanical force sensor when force is applied perpendicular to the plane in upright direction, but firstly the sensitivity S_b (nm/μN) between the corresponding depth of the pillar inserted into the tiny air hole Δh (nm) and the applied force applied perpendicular to the slab plane should be studied. Here, we define S_b as follow:

$$S_b = \frac{\Delta h}{\Delta F} \qquad (3)$$

where $\Delta h/\Delta F$ represents the inserted depth of the pillar caused by specific applied force. Secondly, we define the sensitivity S_c (nm/μN) between the inserted depth (Δh) and the corresponding displacement of resonant wavelength ($\Delta\lambda$) as follow:

$$S_c = \frac{\Delta\lambda}{\Delta h} \qquad (4)$$

where $\Delta\lambda/\Delta h$ represents the shift of the resonant wavelength caused by the inserted depth of the pillar. Finally, combining with Eq. (3) and Eq. (4), the sensitivity in upright direction S_d can be achieved as follow:

$$S_d = S_b \times S_c = \frac{\Delta h}{\Delta F} \times \frac{\Delta\lambda}{\Delta h} = \frac{\Delta\lambda}{\Delta F} \qquad (5)$$