THREE DIMENSIONAL MULTIFUNCTIONAL NANOMECHANICAL PHOTONIC CRYSTAL SENSOR WITH HIGH SENSITIVITY BY USING PILLAR-INSERTED ASLANT NANOCAVITY RESONATOR

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ABSTRACT

We propose a method to detect nanomechanical variations in the three dimensional space with a shoulder-coupled pillar-inserted aslant photonic crystal nanocavity resonator. FEM and 3D-FDTD simulation software are employed to investigate the sensing characteristics. With high quality factor of the aslant nanocavity and the optimized structure, high sensitivity of nanomechanical sensing can be achieved in three dimensions and the limitation of the smallest detectable variations is ultra small. For its ultra small size and ultra high sensitivity in every dimension, this versatile nanomechanical sensor can be widely used in MEMS.

Keywords: *Sensor, Photonic crystals, Resonators, Three-dimensional nanomechanical sensing, Waveg-uides, nanocavity.*

1. INTRODUCTION

Nanomechanical sensor plays a very important role in microelectromechanical system (MEMS) for its ability to detect nano-stress, nano-displacement, nano-deformation and so on. In the past a few years, with the development of fabrication techniques in MEMS, some nanomechanical sensors based on carbon nanotube [1] or fibers [2] have been reported. But there is an obstacle in integrating these devices with silicon devices. In order to obtain high sensitivity; and convenience to be integrated and micro-scale size, optical nanomechanical sensors based on photonic crystal (PhC) have been widely utilized in MEMS. PhC has made it possible for its ultra-small size, high sensitivity and ease of integration. Various kinds of sensors based on PhC have been reported recently such as biochemical sensors [3], gas sensors [4] and temperature sensors [5]. Nanomechanical sensors based on PhC have been widely researched [6-10] and ultra high sensitivity has been achieved. For example, T. W. Lu *et al.* [6] present the design principles to achieve a highly sensitive optical stress sensor based on double-layered photonic crystal microcavity, D. Yang *et al.* [7] proposed a microdisplacement sensor formed by a fixed and mobile hole-array–based triangular lattice slot photonic crystal components with high-Q factor nanoscale cavity and B. T. Tung *et al.* [8] investigated the strain sensing effect of a two dimensional photonic crystal nanocavity resonator. D. Yang *et al.* [9] investigated a novel nanoscale torsion-free photonic crystal pressure sensor based on the side-coupled piston-type microcacity and Y. Yang *et al.* [10] proposed a method to detect nano-stress in two dimensions within a single PhC structure. However, these sensors can only detect the nanomechanical variations in one dimension or two dimensions, and they are difficult to be integrated to realize sensing of the mechanical variation in three dimensions. In order to overcome this drawback and realize three dimensional nanomechanical sensing within one structure, here we propose a novel structure design based on a photonic crystal pillar-inserted aslant nanocavity resonator (PhC-PINR) and the ability to detect nanomechanical variations in three dimensions has been theoretically analyzed.

2. SENSING STRUCTURE DESIGN

The whole size of PhC-PINR structure is 12μm×10μm×2μm and it is ultra small for integration in MEMS. The whole structure consists of two parts, which are the triangular lattice silicon PhC slab and a single Si pillar bonded with a Si panel located above the PhC slab as shown in Fig. 1(a). It's free to sense nanomechanical variations in every direction. The PhC structure is formed by an optimized aslant nanocavity, which is shoulder-coupled by the input waveguide and the output waveguide. Fig. 1(b) shows that the detail of the aslant cavity. The lattice constant a=417nm, radius of bulk air holes r=125nm, thickness

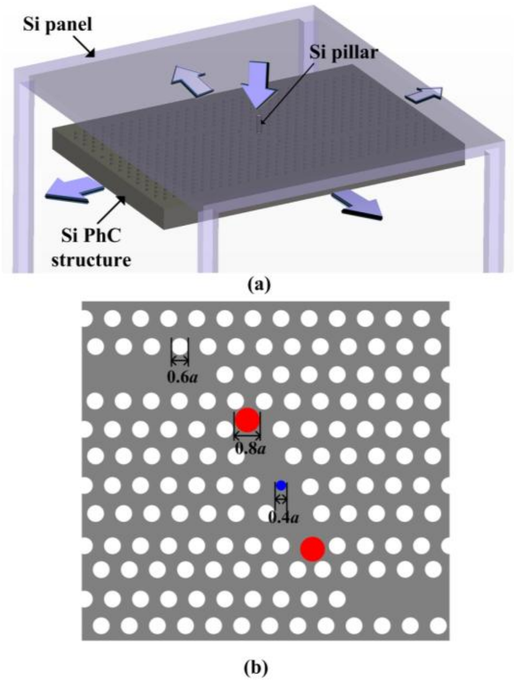

Fig. 1 (a) Schematic of PhC-PINR and the directions of physical variation applied. (b) Details of the PhC aslant nanocavity.

of Si slab t=234nm and the refractive index of silicon n=3.48. The radius of the two outer holes has been adjusted and a smaller air hole is added in the center of the cavity. Here we define the sensitivity (S) of this nanomechanical variations sensor as follow:

$$S = \frac{\Delta\lambda}{\Delta V} \quad (1)$$

where $\Delta\lambda/\Delta V$ represents the displacement of resonant wavelength caused by the nanomechanical variation of the structure. The variation can be external force, displacement, acceleration, weight and so on.

Moreover, we can define the limitation (L) of the smallest detectable variation as follow:

$$L = \frac{\lambda_c}{SQ} \quad (2)$$

where λ_c represents the resonant wavelength and Q represents the quality factor of the aslant nanocavity.

Based on Eq. 1, in order to obtain high sensing sensitivity, high quality factor is needed. And we optimized the nanocavity by adjusting outwards shift displacement of the two outer holes, radius of the two outer holes and the radius of the center tiny hole. The quality factor of this aslant cavity reaches ~8,000.

When nano-acceleration, nano-displacement, nano-force or nano-weight is applied on the structure in the three dimensional space. The shape of the slab or the panel would be varied. The deformations of the PhC-PINR under horizontal and vertical direction variations are shown Fig. 2(a), respectively, the deformations of the sensing structure caused by the

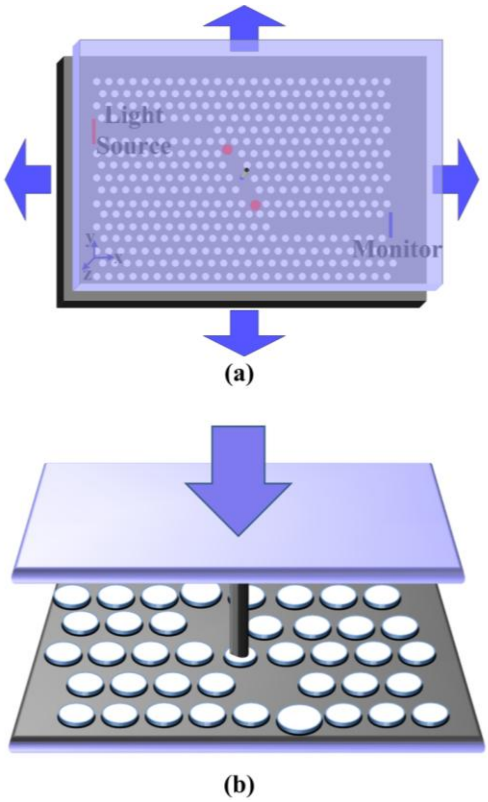

Fig. 2 (a) The deformations of the PhC-PINR under horizontal and vertical direction variations. (b) The deformation of the panel and the pillar under upright direction variation.

physical variations will lead to some variations of the optical properties. When physical variations are applied in the upright direction, the deformation of panel is shown in Fig. 2(b) and the pillar would be inserted into the center air hole in the middle of the nanocavity. All the structural variations lead to shift of specific resonant wavelength in transmittance spectra. The extensive simulation results demonstrate that the resonant wavelength of the mode localized in the nanocavity shifts its spectral peak position following a linear behavior when the physical variations are applied on the structure changes in any dimension. We should emphasize that the sensor functions to detect nanomechanical variations in three dimensions and the sensitivity in every dimension is at the same high level.

3. SIMULATIONS AND DISSCUSSION

3.1 FEM simulation

We use commercial FEM software ANSYS^{TM} 13.0 to construct 3D solid structure and then external physical variation is applied on the structure in three orthometric directions, respectively. All the nanomechanical variations lead to the deformations of the structure and all the variations are equal to the displacement of every element on the PhC slab or the pillar. The deformations under different value of

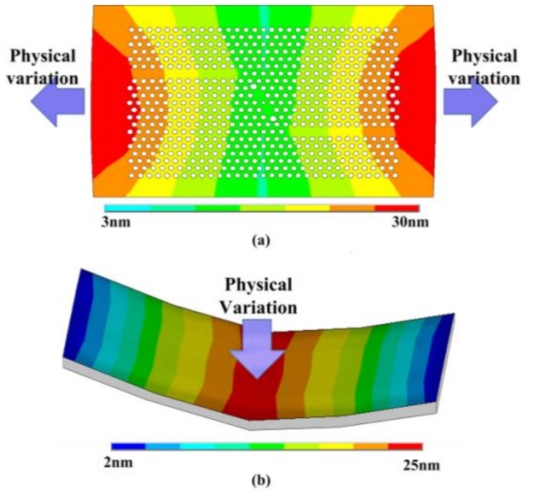

Fig. 3 (a) Deformation contour plot of the structure under 30nm of displacement on the edges in horizontal direction. (b) Displacement in upright direction of the Si panel under physical variation in upright direction.

external physical variations from different directions have been simulated. The detailed parameters are going to be set in the following FDTD simulations for getting transmittance spectra. When the physical variation is applied in horizontal or vertical direction, only the Si slab PhC structure varies and there is no variation on the single Si pillar. Therefore we simulate the deformation of the Si slab PhC structure without the pillar for simplicity when the physical variation is applied in horizontal or vertical direction. We simulate the deformations of the slab PhC structure when the edges of the slab have a displacement resulted from a sort of external nanomanchenical variations under different values in these two directions. As shown in Fig. 3 (a), the displacement of every elements on the slab has been clearly indicated when 30nm of displacement on the edge is introduced in horizontal direction. We can see the variation in the middle of the slab is slight, but the high quality factor aslant microcavity ensure big resonant wavelength shift under tiny variation in the cavity region. The same as applied in horizontal direction, the deformation caused by physical variation applied in vertical direction is similar with the deformation in horizontal direction which is just rotated by 90 degree. With the simulation results in section 3.2, the shift of resonant wavelength versus the value of external physical variation in these two directions is linear, respectively. Thus this structure can be used to sense nanomechanical variations in these two dimensions.

When the physical variation is applied in upright direction, the Si pillar would be inserted into the center tiny air hole in the aslant cavity region with the bend of the Si panel. As the pillar is bonded on the Si panel, the displacement of panel's center area in the upright direction is the same as the displacement of the pillar. Therefore we simulate the panel with a pillar and the displacement of element at the center of the panel is used as the inserted depth of the pillar. The top view of the panel's deformation under physical variation in upright direction is shown in Fig. 3 (b) with the displacement of the middle is 25nm. With a lot of simulation results, the relationship between inserted depth and the variation is found to be linear. Thus this structure can be used to sense nanomechanical variations in this dimension.

3.2 FDTD simulation

All the different parameters of sensing structure under different displacement were put into open source 3D FDTD software-Meep to analyze the variation tendency of the resonant peak.

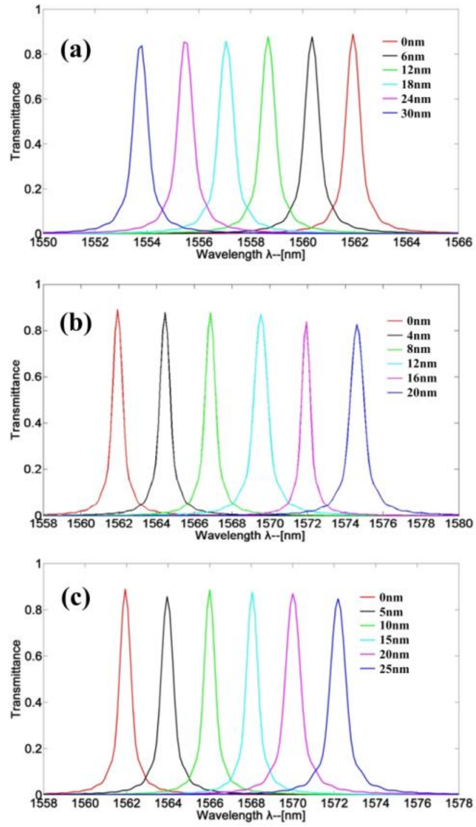

Fig. 4 Shift of resonant wavelength under different values of physical variations in horizontal direction (a), vertical direction (b) and upright direction (c).

As shown in Fig. 4 (a), (b) and (c), the shift trend of resonant peak is linear in three dimensions. It can be seen that the peaks are evenly distributed when the corresponding displacement caused by physical variation increases in three directions, respectively. Therefore when nanomechanical variation is applied in certain direction, by observing the shift of the resonant peak we could evaluate the value of the displacement of the edge of the slab or the center area of the panel. Then corresponding value of the physical variation can be calculated.

3.3 Results discussion

In summary, due to the aslant cavity design with a Si pillar hanging up on the slab, the structure has the ability to detect nanomechanical variation in the three dimensional space. We have demonstrated that the operating principle of the 3D nanomechanical sensor. As all kinds of nanomechanical variations will introduce shift of the resonant wavelength, we could calculate the sensitivity of this sensor and then deduce the sensitivity of certain kind of nanomechanical variation sensing. From data in Fig. 4 and Eq. 1 we can calculate that the sensitivity of this nanomechanical sensing structure expressed with the nano-displacement form is 273 pm/nm, 625 pm/nm and 436 pm/nm in horizontal direction, vertical direction and upright direction, respectively. Moreover, with Eq. 2, the limitation of the smallest detectable nano-displacement is 0.7nm, 0.3nm and 0.5nm in three dimensions, respectively.

For this sensor can be versatilely used in MEMS, the study of this structure is valuable and meaningful. In the future research, well optimized cavity could improve the quality factor substantially and improve the sensitivity consequently. The structure is easy to be integrated as large-scale sensor arrays because it's made of silicon.

4. CONCLUSION

In this paper, we have demonstrated a novel design which can be used to detect multiplex nanomechanical variations such as nano-pressure, nano-displacement and nano-acceleration in the three dimensional space. The structure which formed by an optimized photonic crystal aslant nanocavity and a single thin silicon pillar is ultra small. Ultra-high sensitivity in every dimension is obtained and at the same level. With FEM and 3D FDTD simulations, robust sensing properties have been achieved. Therefore, the structure we proposed here may enhance the highly-sensitive performance and multiplex the capability of PhC nanomechanical sensors.

5. ACKNOWLEDGMENTS

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