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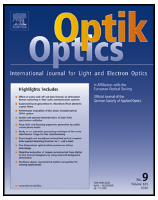

Full length article

Photonic crystal ring resonator based force sensor: Design and analysis

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ABSTRACT

In this paper theoretical investigation of photonic crystal based force sensor is presented. Photonic crystal ring resonator design is optimized for the improvement of quality factor considering the fabrication feasibility. For the optimized configuration a high quality factor of 15500 is obtained and it is found that it remains constant over the desired force range. The minimum detectable force is found to be 9 nN for 0.1 nm wavelength resolution. A high sensitivity of 11 nm/μN is obtained in the studied force range.

1. Introduction

Photonic Crystals (PC) are the periodic optical structures with periodic refractive index variation that affects the motion of light in much the same way that periodic lattices affect electrons in solids. Among these, two dimensional PC slabs with periodic array of air holes are attractive, as they are relatively easy to fabricate compared to the three dimensional PC devices and capable of guiding light effectively in all the three dimensions [1–3]. By fine tuning and controlling the parameters of these PC slabs, many devices are reported such as PC resonator based bio sensors [4,5], channel drop filters [6], refractive index sensor [7], PC slow light devices [8–12]. Apart from these devices, PC devices embedded in microcantilever structures are promising, since they are extremely sensitive to surface deformations and refractive index variations on the surface of cantilever beam. Various PC devices on microcantilever structures for different applications were proposed, as discussed below.

An ultra high stress sensitive dual layered InGaAsP PC micro cavity is reported [13]. This structure consists of two PC beams separated with air gap. The minimum detectable stress variation is estimated as small as 0.95 nN. If sensitivity and quality factor of individual PC beams are improved, then the device will be even more sensitive. In the recent past, various cantilever beam sensors integrated with PC devices are proposed. C Lee et al. presented a PC based nano cavity resonator with a minimum detectable force of 62.5 nN [14]. A PC ring resonator integrated on top of Si/SiO_2 bilayer cantilever [15] is reported. The reported minimum detectable force is 76 nN for 0.1 nm wavelength resolution with a Q of 3500. On the other hand, PC dual ring resonator integrated on a Si cantilever based sensor with various configurations is proposed [16,17].

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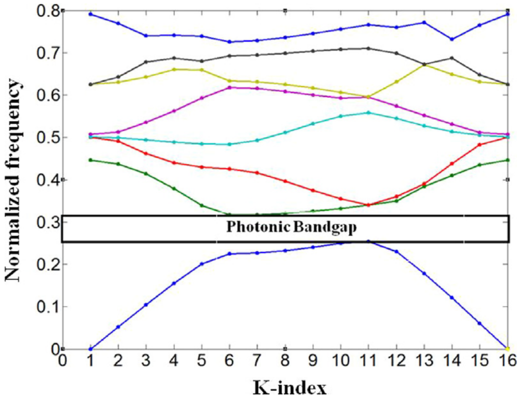

Fig. 1. Photonic Bandstructure of the considered photonic crystal without defects.

Among these configurations the most sensitive configuration gives a minimum detectable force of 7.58 nN in a particular range of applied force, whereas the quality factor was found to be reduced drastically. Apart from these devices with point defects and ring resonator cavities, a shoulder coupled aslant nano cavity based PC stress sensor is proposed, which is capable of sensing in two directions [18]. In horizontal and vertical directions, the sensitivity is found to be 7.5 nm/μN and 10 nm/μN respectively with a Q factor of 3000. Since quality factor plays crucial role in all the above mentioned sensing applications, Q factor enhancement is of major concern considering the design constraints and fabrication feasibility.

In recent years many designs are reported for the improvement of quality factor of a PC based device. High Q resonators are designed by increasing or decreasing the hole sizes, moving the holes around the cavity, removal of holes, addition of extra scatter holes, so that most of the components in the momentum (K-vector) space are pushed away from the light cone region [19–21]. Zhang Y et al. reported a high quality factor photonic crystal ring resonator, with scattering holes in the corners of the hexagonal ring [22]. A high quality factor of 121000 is achieved with a PC ring of large dimension. Even though high quality factors are achieved, when these devices with high Q cavities are surrounded by line defect waveguides, the boundaries of the cavity are altered and hence the K-space distribution, leading to drastic reduction in quality factor. This happens because of the inclusion of more k-space components within the light cone region. This effect can be reduced up to some extent by increasing the coupling distance between the cavity and the bus waveguides, but this leads to poor coupling between them. In order to avoid this problem, one alternate design is proposed in which the quality factor is made independent of the surroundings of the cavity [23]. This cavity design consists of a larger central hole, which is surrounded by hexagons of air holes with decreasing radii along the outward direction. This variation of radii of holes in each hexagon is given by a parabolic relation. The variation in size of the holes fine tunes the cavity, so that two different modes of the cavity become degenerate with equal quality factor. In the similar manner, an optimized PC ring resonator with super defect is proposed to exhibit improved Q factor [24]. The improvement in Q is explained based on forced far field cancellation mechanism.

In the present work, a new approach is adopted to get optimal quality factor for a PC ring resonator based force sensor. The main focus is on improving the quality factor of the resonator and keeping it constant for all applied forces of interest. This is achieved by optimizing the air hole radii inside the PC ring resonator. The increase in quality factor is explained by analysis of E-field distribution in momentum space. The design of the sensor consists of two phases. In the first phase 3D Finite-difference time-domain (FDTD) simulations are performed to get the optimized PC resonator design. The second phase consists of Finite Element Method (FEM) simulations to get the deformation data of cantilever surface for various applied forces. For each applied force, FDTD simulations are performed to get the spectral characteristics of the deformed PC device. The second section is dedicated for design and optimization of the PC ring resonator. The force sensing capabilities of the PC ring resonator on cantilever are discussed in the third section. In FDTD simulations we used mesh size of 0.0205 μm, 0.0178 μm and 0.015 μm in X, Y and Z directions respectively.

2. Design, analysis and optimization of photonic crystal ring resonator

In our design, a 220 nm thick silicon PC with hexagonal lattice of air holes is used. Hexagonal lattice is chosen since it provides wider photonic band gap compared to square lattice. The lattice constant and air hole radius are chosen to be 410 nm and 120 nm, respectively. The band structure of the considered PC structure is shown in Fig. 1. As shown in the figure, there is a bandgap in the normalised frequency range of 0.26–0.32, correspondingly in the wavelength range of 1250 nm–1600 nm. The proposed PC ring resonator consists of a hexagonal ring formed on the PC slab. The hexagonal ring is formed by removing the air holes on the slab in hexagonal shape and also line defect waveguides are formed on either side of the ring as shown in Fig. 2. The PC resonator consists of four different ports namely input port, transmission port, forward drop and backward drop. The line defects are bent on either side in such a way that there will be sufficient gap between the ports that lie in the same side. This is to avoid cross coupling of light at those ports during characterisation of the PC device.