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Simultaneous detection of refractive index, temperature and stress realized by using a three-mode planar photonic crystal L5 cavity

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ABSTRACT

A multifunctional sensor that can detect multiple parameters simultaneously is proposed in this paper. The sensor is based on a well-designed planar photonic crystal (PPC) L5 micro-cavity, which is capable of producing three resonant modes. Each mode of the cavity responds distinctively to different external perturbations, rendering the multi-mode cavity (MMC) superior capabilities for multi-parameter sensing. By using three dimensional finite difference time domain (3D-FDTD) simulation method, Q-factors and extinction ratios of these three modes are carefully optimized. Afterwards, refractive index (RI) sensing, temperature sensing, and vertical stress sensing based on the MMC are realized respectively. Finally, by constructing a sensing matrix, three parameters detection can be achieved simultaneously, and the crosstalk between sensing parameters is discussed. The multifunctional sensor can greatly improve the on-chip integration of photonic crystal sensing networks and will have broad application prospects.

1. Introduction

Among all sorts of nanostructure sensors, photonic crystal (PhC) sensors have obtained special attention from many researchers in different fields of application, due to their merits such as high sensitivities, high resolutions, fast response, small size, easy integration and so on. Sensors based on PhC devices such as PhC line defects [1,2], PhC micro-cavities [3–5], and PhC ring resonators [6,7] are widely used in biochemical sensing [8–11], pressure sensing [12,13], temperature sensing [14,15] and other fields. In order to improve the on-chip integration of sensing networks, PhC sensors have undergone the development of multi-cavity multi-point detection [16–19] from single-cavity single-point detection [20–22] in the past decade. However, whether for the single point detection or multi-point detection, the detected parameter is usually unitary, without further consideration of functional multiplexing.

The traditional sensors based on PPC micro-cavities typically only use one resonant mode for sensing [23–25]. However, multiple optical modes localized in a single PPC micro-cavity have the potential of being used simultaneously for sensing. Through effective micro-cavity structure design, PPC micro-cavity can generate multiple resonant modes, and each mode can meet the sensing requirements by optimizing its optical characteristics. What is more, each resonant mode of MMC has different sensitivities of external stimuli due to different intensities of light-matter interaction among the modes. Finally, by constructing a sensing matrix, simultaneous detection of multi-parameter can be realized. The multifunctional sensor can greatly improve detection efficiency, simplify sensor structure and save cost. Therefore, the proposed sensor will have broad application prospects, such as marine monitoring, natural gas pipeline monitoring and so on, in which the environmental parameters are complicated.

In this paper, a multi-mode L5 cavity based on PPC structure is designed to realize refractive index, temperature and stress simultaneous sensing. The well-designed cavity can generate three resonant modes, and the Q-factor and extinction ratio of each mode are carefully optimized. Afterwards, different kinds of parameters sensing has been analytically and numerically discussed by using 3D-FDTD and finite element method (FEM) simulations. Finally, a multi-parameter multiplexing sensing model is proposed, and the crosstalk between different parameter sensing is well discussed.

2. Design of multi-mode L5 cavity in PPC structure

The Ln point defect based cavity in a PhC slab is one of the most widely accepted micro-cavity designs because of its relatively high Q-factor and very small mode volume [26,27]. In this paper, the proposed

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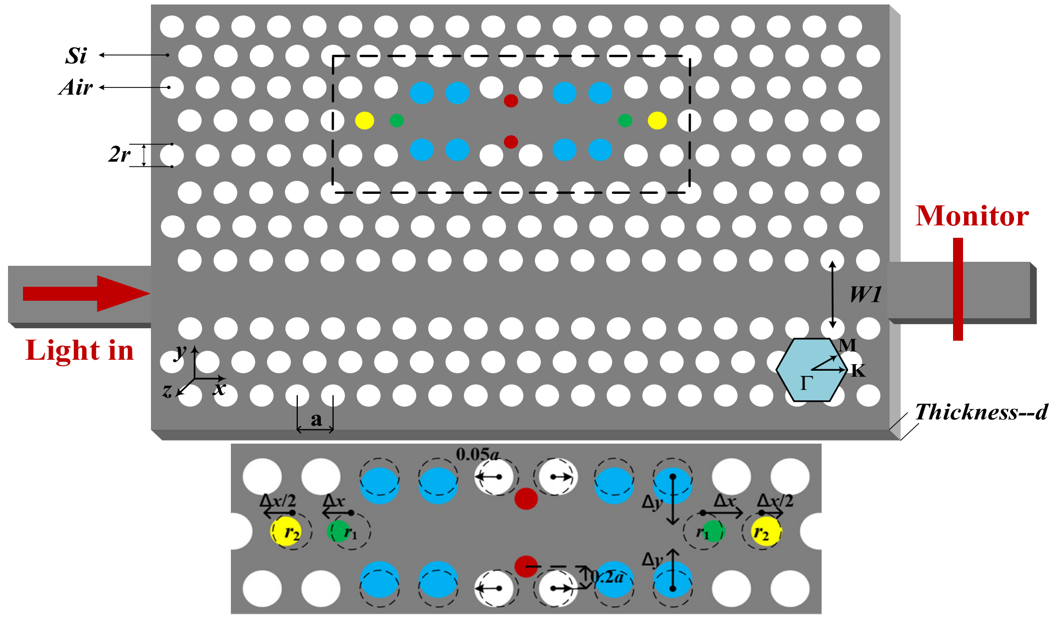

Fig. 1. Schematic of the proposed sensor structure, and the detail view of the multi-mode L5 cavity is shown below, black dotted circular hole indicates the initial positions and sizes of the air holes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sensor structure is based on a L5 defect of PPC, as show in Fig. 1. The PPC structure is constructed in a silicon slab (n_{si} = 3.48) by arranging a triangular lattice of air holes. The lattice constant is a = 400 nm, the radius of air hole is $r = 0.25a = 100$ nm, and the thickness of silicon slab is $d = 0.55a = 220$ nm. The L5 cavity is side coupled to a W1 waveguide (4 lines away), which is formed by removing a line of air hole of the PPC structure. The TE-like polarization light source is set at the head of the input waveguide and the power monitor is located at the end of the output W1 waveguide.

We study and optimize the proposed structure design by using commercial 3D-FDTD software (FDTD Solutions, Lumerical). In 3D-FDTD simulation, the time step is 0.0578651, the simulation time is set as 70,000, and the convergence condition for simulation uses early shutoff, auto shutoff min is 10^{-6}. The computation environment is shown as following, the processor is a dual-core processor: Intel(R) Xeon(R) CPU E5-2640 0 @ 2.50 GHz 2.50 GHz, and the RAM memory is 56.0GB. Computation time of one simulation needs around 16 h. The source is chosen mode source, and fundamental TE mode is selected. The simulation dimension is 3D, and the simulation area is surrounded by perfectly matched layer (PML), which absorbed the fields leaving the simulated region in order to prevent reflections. In FDTD Solutions, the Q factor for high Q factor cavity is calculated by:

$$Q = {-\omega_r \log 10(e)}/{2m} \quad (1)$$

where ω_r is the resonant frequency, m is the slope of the log of the time signal envelope.

The normal L5 cavity can only generate two resonant modes stably. In order to make the L5 cavity generate the third resonant mode, we have managed to enlarge the L5 cavity body by moving outward two adjacent air holes on both sides of the cavity. As shown in Fig. 1, the displacement of the two air holes are given by Δx and $\Delta x/2$, respectively. When Δx varies from 0 to $0.5a$, the Q-factor and extinction ratio (ExT) of each mode are calculated and shown in Table 1. The asterisk represents that the second-order mode is not generated when Δx is equal to corresponding values, thus, there is no relevant data. The results show that the generation of second-order mode requires the size of the L5 cavity to satisfy certain boundary conditions. At the same time, it can be clearly seen that with the increase of Δx, the area of high RI part in L5 cavity increases, making each mode of the cavity has a red-shift trend at the beginning, and then when the second-order mode declines, the resonant wavelength of the fundamental and first-order modes is slightly decreased. In addition, as Δx varies, for the fundamental mode, the Q-factor increases while the extinction ratio is getting larger. For the first-order mode, the Q-factor changes insignificantly, but the extinction ratio firstly decreases and then increases. For the second-order mode, the Q-factor and extinction ratio reach the optimal value at the same time. On account of the trade-off between Q-factor and extinction ratio, Δx is set as $0.4a$.

As revealed in Table 1, the Q-factor of first-order mode is relatively low compared to the other modes when Δx is determined to be $0.4a$. So that the next step optimization is made to improving the Q-factor of first-order mode. By observing the electric field intensity patterns (Fig. 4(b)) of the first-order mode, we can know that the air holes near the electric field (blue air holes shown in Fig. 1) have the greatest effect on the properties of first-order mode. Then we can further optimize the performance of the first-order mode by tuning the positions of these holes. As shown in Fig. 1, the displacement of the blue air is given by Δy. With different values of Δy, Q-factors and extinction ratios of these three resonant modes are shown in Fig. 2(a) and (b). When Δy equals to 40 nm, the first-order mode reaches the maximum Q-factor, while the Q-factors of the fundamental and second-order modes remain relatively high. So that in our design, Δy is chosen to equal to 40 nm. What is more, as the Δy increases, the area of high RI in L5 cavity decreases, therefore the resonant wavelengths have a blue shift, which is shown in Fig. 2(c).

While for sensing applications, in order to facilitate detection, the extinction ratio of the resonant dips should be as small as possible. As shown in Fig. 2(b), extinction ratios of the first-order and second-order modes are relatively high when Δy equals to 40 nm. So the third step optimization is mainly made to improve the transmittance of higher-order modes. By reducing the radii r_1 of the green air holes and the radii r_2 of the yellow air holes shown in Fig. 1, transmittance of the first-order and second-order modes can be remarkably improved. First, as shown in Fig. 3(a), the transmittance of the higher-order modes increases significantly when r_1 decreases, and the position of the resonance dip shifts to a larger wavelength. The specific extinction ratios are also calculated and shown in Fig. 3(c). When r_1 is reduced to $0.6r$, the extinction ratio correspondingly decreases 135% for the first-order mode, and 125% for the second-order mode. And then, keeping $r_1 = 0.6r$, r_2 is changed to further improve the transmittance of higher order modes as shown in Fig. 3(b) and (d). And when r_2 is less than