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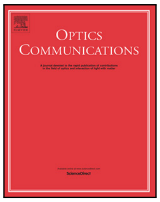

Multiplexing dual-parameter sensor using photonic crystal multimode nanobeam cavities

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ABSTRACT

In this paper, we theoretically propose an ultra-compact low crosstalk photonic crystal dual-channel sensor (DCS) for multiplexing dual-parameter sensing. To begin with, a photonic crystal (PhC) elliptical holes multimode nanobeam cavity (EMNC) is designed. By applying three-dimensional finite-difference time-domain (3D-FDTD) simulations, high Q-factors above 1×10^6 of 0^{th}-order mode and 1×10^5 of 1^{st}-order mode can be simultaneously achieved. Next, a well-designed equal power splitter, a power combiner and two EMNCs are introduced to form a PhC dual-channel sensor. Based on a sensing matrix, each channel of DCS (EMNC-1 and EMNC-2) can be used in simultaneous detection of refractive index (RI) and temperature independently. Particularly, the total footprint is only about 26.5 μm ×6.2μm ×0.22μm (length × width × high), which is potentially a promising platform for complex optical multi-sensing network in large scale.

1. Introduction

Owing to the great capability to manipulate light propagation, lab-on-a-chip optical devices utilizing photonic crystal (PhC) are attractive in various applications. Particularly, PhC sensors seem to be very promising in lab-on-a-chip applications, because of their ultra-compact sizes, small footprints, low power consumptions and fitting in monolithic integration. Recently, PhC sensors using one resonant mode have been widely applied in refractive index (RI) sensing [1–3], temperature sensing [4–6], pressure sensing [7] and biochemical sensing [8–11].

With the development of sensing research, dual-parameter sensing has drawn extensive attentions, because the cross sensitivity should not be neglected when the selected resonant mode of the optical sensor for sensing is sensitive to other parameters [12]. In order to achieve simultaneous detection, different devices have been developed, such as interferometers [12,13], fiber sensors [14,15], micro-ring resonators [16,17] and so on. However, these dual-parameter sensor devices are commonly large in size and complex in design. As for PhC dual-parameter sensor, the device of a H0-cavity and a H1-cavity cascaded together [18] and the device using side-coupled PhC nanobeam cavities [19] have been reported. However, these devices consist of two resonators, which makes it difficult to realize high-density monolithic integration.

In addition, the common drawbacks of these dual-parameter sensors are that they typically operate as point or single sensing and only one target can be analyzed at one time. Over the years, integrated photonic crystal sensor array has been demonstrated as an effective method to realize multiplexing sensing. Lots of different PhC sensor array structures with excellent performances have been proposed [20–24]. It is noteworthy that multi-channel sensor arrays based on two-dimensional (2D) PhC are usually very large and difficult to realize low crosstalk integration. Compared with them, one-dimensional (1D) PhC nanobeam cavities possess many advantages, like higher quality factor (Q), smaller mode volume and higher integrability, which make them considered as ideal candidates for the investigations of lab-on-a-chip optical sensors. For example, Sun *et al.* [25] reported an air-mode PhC nanobeam cavity with an ultra-high Q-factor of 7.2×10^6. Huang *et al.* [26] proposed a PhC low-index mode nanobeam cavity sensor with a Q-factor $\sim1.35 \times 10^5$ and a high sensitivity (S) ~390 nm/RIU (refractive index unit). Yang *et al.* [27] proposed a novel 1D PhC nanobeam cavity sensor array with excellent multiplexing capability. Whereas, these above-mentioned PhC nanobeam sensors only focused on RI sensing.

In this paper, we propose an ultra-compact low crosstalk photonic crystal dual-channel sensor (DCS) whose each sensing channel is qualified for dual-parameter sensing, to overcome above-mentioned limitations. The ultra-compact device consists of a 1 × 2 equal power splitter, a 2 × 1 power combiner and two high-Q PhC elliptical holes multimode nanobeam cavities (EMNC). The optimization of PhC nanobeam cavity and sensor array are investigated numerically with three-dimensional

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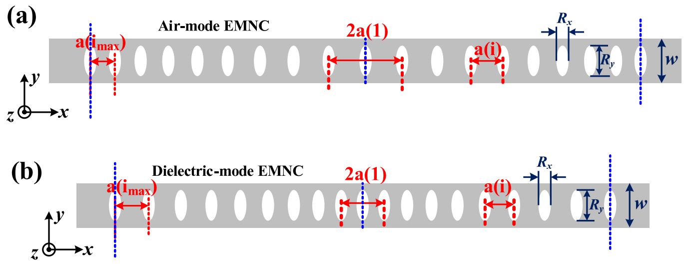

Fig. 1. Schematic of (a) air-mode EMNC and (b) dielectric-mode EMNC. The structure is symmetric with respect to its center (blue dashed line). The major axis (R_y) and the minor axis (R_x) of the ellipse holes are kept constant. The lattice space is quadratically modulated from a (1) to a (i_{max}) on both sides. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

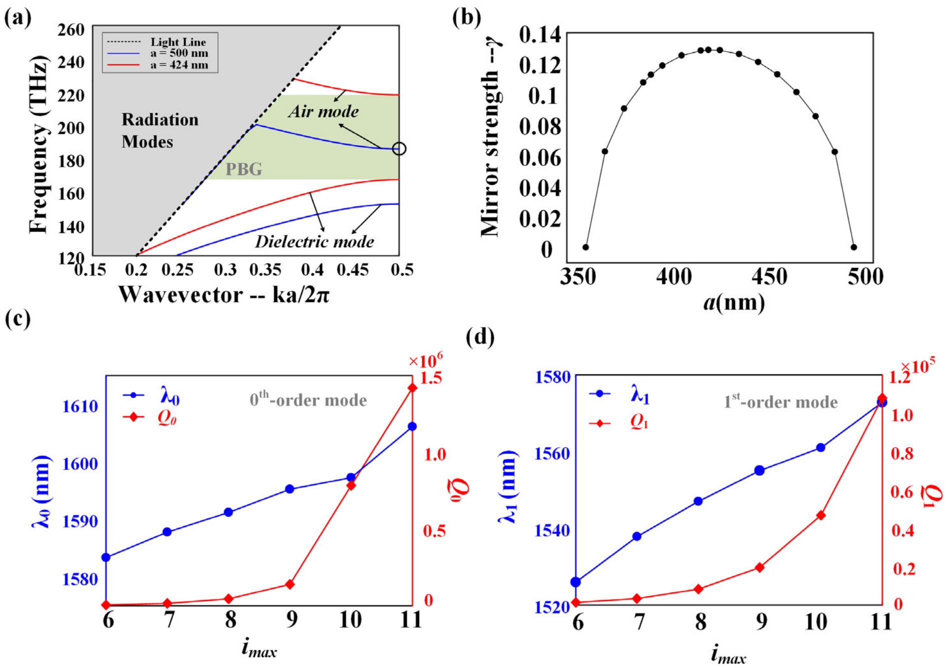

Fig. 2. (a) TE band diagram of the air-mode EMNC with a = 500 nm (blue line) and a = 424 nm (red line). The circle indicates the target resonant frequency. (b) Mirror strengths (γ) at different lattice spaces (a) obtained by 3D band diagram simulations. (c)–(d) Resonant wavelength and Q-factor of (c) 0th-order mode (λ_0, Q_0) and (d) 1st-order mode (λ_1, Q_1) as a function of i_{max} obtained by 3D-FDTD simulations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

finite-difference time-domain (3D-FDTD) method. Firstly, we design a PhC EMNC by tapering the lattice space of elliptical holes from the center to both ends quadratically, while other structural parameters remain. Ultra-high Q-factors above 1×10^6 of 0th-order mode and 1×10^5 of 1st-order mode can be achieved when 11 elliptical holes are placed at both sides. Secondly, two EMNCs with different lattice spaces are connected in parallel by placing a 1 × 2 equal power splitter and a 2 × 1 power combiner at the input and output port, to form the low crosstalk DCS. Followed by the definition of sensitivity, sensitivities of EMNC-1 are as follows: $S_{n,0}$ = 233.75 nm/RIU, $S_{n,1}$ = 216.23 nm/RIU, $S_{T,0}$ = 70.5 pm/K and $S_{T,1}$ = 69.5 pm/K. Meanwhile, sensitivities of EMNC-2 are as follows: $S_{n,0}$ = 112.5 nm/RIU, $S_{n,1}$ = 135 nm/RIU, $S_{T,0}$ = 75 pm/K and $S_{T,1}$ = 76.5 pm/K. Based on a sensing matrix and our observing resonant wavelengths of 0th-order and 1st-order modes, each channel of DCS can be used in simultaneous measurement of RI and temperature independently. Compared with the previous dual-parameter sensors, our DCS not only has a much smaller footprint of 26.5 μm × 6.2 μm × 0.22 μm (width × length × height), but also gets the application in dual-parameter simultaneous detection of multi-analytes on a monolithic silicon chip accomplished. To summarize, both the DCS structure and the general idea have profoundly instructive meaning in the development of large-scale on-chip sensing system.

2. Design and optimization

We design and optimize PhC nanobeam cavities and PhC sensor array by using commercial 3D-FDTD software (FDTD Solutions, Lumerical).

2.1. PhC EMNC design

Generally, the optical modes of air-mode cavities locate in a shorter wavelength region in the spectrum, while the resonant modes of dielectric-mode cavities locate in a longer wavelength region [28]. Therefore, after introducing these two kinds of PhC nanobeam cavities into a sensor array simultaneously, we are able to make a better management in utilizing photonic band gap (PBG). In this section, these two kinds of EMNC are investigated, respectively.

Fig. 1(a) shows the schematic of the air-mode EMNC, and Fig. 1(b) represents the dielectric-mode EMNC structure. They consist of an array of elliptical air holes with the same dimension. The major axis (R_y) of the ellipse hole is 500 nm and the minor axis (R_x) equals to 200 nm. These elliptical air holes (n_{air} = 1.00) are etched onto a silicon (n_{si} = 3.48 at 300 K) strip waveguide with a width w of 700 nm and a thickness h of 220 nm. Meanwhile, the whole device is symmetric with respect to the blue dashed line in Fig. 1.