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Various photonic crystal bio-sensor configurations based on optical surface modes

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ABSTRACT

We design a new bio-sensor concept that incorporates photonic crystal (PC) surface modes to sense small refractive index changes. The initial attempt creates optical surface modes by first enlarging and then perforating the radii of rods residing along the end surface of the square-lattice PC. The strongly confined mode which decays both evanescently along transverse to propagation direction interacts with the substance while propagating along the PC-air interface. Due to index change of the ambient medium, the transmission spectrum experiences linear shift with a large dynamic range. The relocation of the surface defects enhances the sensitivity of bio-sensor from ∼8 to ∼93 nm/RIU. The second type of investigated PC structure is based on triangular-lattice PC and it provides a surface state bio-sensor with a sensitivity of 117 nm/RIU. In addition to these designs, we propose a final structure that incorporates air slot along one side of triangular-lattice PC. We succeeded to obtain a new sensitivity value of 396 nm/RIU. The investigation shows that even higher sensitivities can be achieved. The different RIU values are reminiscent of group velocity of the relevant modes which can be extracted from the dispersion analysis. Compact, sensitive and label-free optical sensors based on surface modes may become part of the important applications in opto-fluidic technology and lab-on-a-chip.

1. Introduction

Operating principle of an optical bio-sensor is based on the interaction of light waves with the targeted materials that need to be detected. When light wave encounters the targeted objects such as bio-molecules, chemical substances or gas molecules, the resonance frequency of the resonator or the transmission window of the waveguide system shifts due to change of the refractive index of the material. There are many different versions of bio-chemical sensors that utilize different sensing platforms. The current work aims to propose and investigate a novel sensor based on photonic crystals (PC). The idea of designing biosensors with PCs has gathered great interests from the researchers [1–13]. PCs are periodic dielectric structures which can be used to cultivate light waves and provide a medium for strong light–matter interaction [14]. One of the desirable features of PCs comes from the intense electric field confinement capability that may occur if certain types of spatial defects are introduced into the otherwise periodic structure. The strong field confinement corresponds to optical modes that appear inside the photonic band gap (PBG), i.e., forbidden frequency interval in the dispersion diagram. This feature can be exploited for the purpose of sensing small amount of analytes [4,10,11,13]. The other crucial feature of PCs with respect to biosensor application is the compact nature of these structures. Once the light strongly interacts with the substance, any change in the refractive index of the material will be monitored via observing optical power spectrum of either the reflected or the transmitted light.

Incident light waves possessing frequencies within the PBG are totally reflected by the PCs. When there is a certain type of defect through a line, light waves within the PBG frequencies can propagate following the defined waveguide path. There can also be a point defect called cavity which can be used for imprisoning the light waves. PC based sensors with a cavity configuration monitor resonance wavelength peak shift. Due to high-Q nature of the cavity, highly sensitive bio-sensors can be obtained [15,16]. On the other hand, monitoring the cut-off band edge movement of transmission window could be possible with the waveguide configuration [1,2,6]. In summary, the two widely investigated aspects of PCs for bio-sensing purpose belong to either cavity or waveguide configuration.

PCs may also support surface modes which can be made by placing some sort of defect along the surface [14,17–20]. These modes are propagating electromagnetic waves which are bound to the interface between PCs and uniform medium such as air. In this paper, we focused on bio-sensor application of surface modes and aimed to show the great potentials of two-dimensional PC sensors based on optical surface waves. The detection criteria are based on relatively broad resonance peak wavelength shift of the output

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power. When the sensing medium changes from air to some type of liquid, the refractive index change occurs depending on the type of the infiltrated substance. The investigated interval for the refractive index change is taken from 1.30 to 1.80.

If a comparison is made between this study and the previous ones, the following advantages of the present approach can be mentioned. Surface mode biosensor requires less sensing area, i.e., analyte needs to be infiltrated into small holes (capillary) or air-slot regions. Some of the other methods start to show nonlinear dependency to refractive index changes. However, the sensitivity in our case shows a large and linear dynamic range. As a result, it may detect a wide range of different liquids. The proposed sensor operates by monitoring the shifts in the wavelength of transmitted light while different liquid infiltrations take place. The presence of the liquid inside perforated rods results in a detectable wavelength change. The penetration depth of the electromagnetic wave plays important role to determine the sensitivity of any evanescent wave sensors. Instead of evanescent wave, direct light-matter interaction is enabled in this work. Finally, the present study allows attaining two identical sensing waveguide branches at the same time. The amount of these branches can be easily increased more than two at will.

The reported highest sensitivity values for the two different PC structures, square- and triangular-lattice, are 93 and 396 nm/RIU, respectively. It would be instructive to provide a performance comparison of the proposed sensor with the literature in terms of RIU sensitivity. It should be noted that we do not pursue to provide a comprehensive and detailed collection of the available work in literature. Ref. [9] reports sensitivity value as high as 410 nm/RIU with a nano-slot photonic crystal cavity configuration. Similarly, Ref. [10] has demonstrated RI sensitivity value of 200 nm/RIU. Even further achievement in RIU sensitivity around 1500 nm/RIU was demonstrated in Ref. [11]. Moderate values of 90 and 100 nm/RIU were the statements of Refs. [12,13], respectively. Considering all these previous studies, it should be emphasized that larger RIU sensitivity is proportional with the quality factor of the resonator type structures. The lower RIU is usually associated with either low-Q cavities or waveguide type of configurations. In this aspect, our reported RIU value of the surface mode sensor is comparable with the previously reported results in the literature.

2. Design of photonic crystal surface mode bio-sensor

To describe the structural parameters of the first type of proposed square-lattice PC bio-sensor, we prepared Fig. 1(a). As can be seen from the plot, the structure consists of dielectric rods which have refractive index of 3.46 and the background is air. The rods are distributed periodically in a square lattice pattern, where the periodicity is represented by the lattice constant, a. It is fixed at 500 nm and the diameter of rod is $d_1 = 200$ nm. The periodicity of the PC is first broken by introducing a line defect along ΓX direction. The consequence of such structural perturbation is the appearance of a waveguide mode that is bounded by the PBG effect. Light wave which has a frequency within the gap can easily propagate through the waveguide. This standard waveguide is implemented to deliver the input signal to the sensing area (end facets of PC).

The surface mode can be supported along the PC-air interface if a certain type of defect is introduced. Considering the biochemical sensor application, the rods along the end surface are first enlarged and then perforated. Hence, they resemble an annular shape with the inner and outer diameters of $d_1 = 200$ nm and $d_2 = 300$ nm, respectively. These modified rods are expected to support surface modes and when the light wave comes to this interface with a right frequency, the electric field should be strongly confined on the surface. The dispersion diagram of photonic structure is calculated by plane-wave expansion method (PWM) [21]. The result is shown in Fig. 1(b), where the thick-solid line inside the PBG region represents the surface mode. It is single mode and well isolated from the air and dielectric continuum bands. That implies the presence of strong field concentration at the interface. The spectral region staying above the light line is shaded in the figure.

The electric field distribution of the relevant mode at both sides of the interface is shown in Fig. 1(c). It has its peak value at the central positions of perforated rods. The evanescent decay behavior is apparent in the figure. Besides, even though it decays evanescently in both directions ($\pm x$), the decay ratios are different due to two totally different medium, PC versus uniform free-space. The temporal characterization of the surface mode bio-sensor will be performed in the next section by using time-domain analysis.

3. Sensing mechanism of surface mode optical bio-sensor

The time-domain analysis is carried out by using two-dimensional finite-difference time-domain (FDTD) method [22]. The computational domain is terminated by perfectly matched layer to prevent back reflections from the boundaries. The spatial resolution of FDTD is set to 30. We measured the transmission spectra of waveguides that are infiltrated with different refractive indices.

To excite the surface mode, we launched a Gaussian pulse whose bandwidth covers the frequency interval of the surface mode. Since the surface mode is band gap guided, it is expected that the same mode can be guided inside a regular PC waveguide (PCW). The source located at the entrance of PCW is transverse magnetic (TM) polarized because band gap only occurs for TM polarization in the square-lattice PC. The electromagnetic field components of TM polarization consist of H_x, H_y, and E_z. The light wave propagates along the standard waveguide and it is equally divided into two parts when it reaches the end. Fig. 1(d)–(f) present a time domain snap shots of three selected cases of optical pulses at different places: specifically, inside the waveguide, around the corner and along the surface of PC.

We can see from these plots that light is confined both inside the PCW and also along the PC-air interface. The excitation of surface mode is efficient despite the fact that there are some back reflections arising from the junctions of waveguide. Some part of the light radiates directly towards the forward direction. More efficient surface mode excitation scenarios can be tackled but this aspect is kept outside the scope of the present work. To monitor the power that couples to surface mode and reaches the end of the surface, the flux plane is placed at the exit of the perforated surface rods. Initially, output power of the structure is plotted by taking the refractive index of the holes equal to 1.0 and this case is taken as a reference. The central peak of the pulse arrives at $\omega a/2\pi c = 0.3757$. When the refractive index is increased from 1.0 to 1.30 the resonance frequency shifts to 0.37512. In the next case, we continued to increase the refractive index up to 1.80 with a step of 0.10 and tracked the resonance frequency shifts, accordingly. The complete pulses with the reference case are shown in Fig. 2(a). It can be seen from the figure that all pulses experience a regular shift to lower frequencies with respect to their resonance frequencies when refractive index increases. Fig. 2(b) summarizes this dependency. There is a linear relation between the resonance shift of the pulse and the refractive index changes.

To judge the performance of the designed surface mode sensor, an appropriate figure of merit (FOM) will be useful. Hence, we use $(\Delta\lambda/\Delta n)$ as a FOM, where $\Delta\lambda$ and Δn represent wavelength and refractive index changes, respectively. The extracted value of FOM from Fig. 2(b) is 7.957 nm/RIU, where RIU stands for refractive-index-unit. We should point out that this FOM may be lower than