Optics Communications 382 (2017) 105–112

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Higher-order mode photonic crystal based nanofluidic sensor

Wang Peng [a,b,c], Youping Chen [a,*], Wu Ai [a]

[a] *School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China*
[b] *Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[c] *Micro and Nanotechnology Laboratory, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*

ARTICLE INFO

Article history:
Received 9 June 2016
Received in revised form
7 July 2016
Accepted 8 July 2016
Available online 6 August 2016

Keywords:
Photonic crystals
Optofluidic biosensors
Label-free detection
Sensitivity

ABSTRACT

A higher-order photonic crystal (PC) based nanofluidic sensor, which worked at 532 nm, was designed and demonstrated. A systematical and detailed method for sculpturing a PC sensor for a given peak wavelength value (PWV) and specified materials was illuminated. It was the first time that the higher order mode was used to design PC based nanofluidic sensor, and the refractive index (RI) sensitivity of this sensor had been verified with FDTD simulation software from Lumerical. The enhanced electrical field of higher order mode structure was mostly confined in the channel area, where the enhance field is wholly interacting with the analytes in the channels. The comparison of RI sensitivity between fundamental mode and higher order mode shows the RI variation of higher order mode is 124.5 nm/RIU which is much larger than the fundamental mode. The proposed PC based nanofluidic structure pioneering a novel style for future optofluidic design.

1. Introduction

PC (Photonic crystal) is a periodic grating structure, with high refractive index guided layer surrounded by lower refractive index layers. Since the initial work of Yablonovitch [1], PCs have attracted increasing interest due to their intrinsic advantages, such as low cost [2], large electrical field enhancement [3], and high sensitivity [4–7]. PCs are usually designed to couple strongly with special optical wavelength according to the materials and the modulated grating period. When matched with the wavelength of resonance, light will be confined strongly to the guided layer and results in an electric field related to the PC many times larger than the field of incident light [8,9]. Since the changing of the ambient medium parameters can induce resonance wavelength shift due to the effective RI variation of the PC, it can vary the distribution of the related evanescent filed. As a result, PC has been used in many different fields including label-free biosensing [10,11], lasing [12], PCEF (photonic crystal enhanced fluorescence) [13], PCEM (photonic crystal enhanced microscopy) [14], and PC micro-fluidics [15,16]. Recently, PC have been utilized to sense ambient refractive index [17,18], protein detection [19], and antibody in the micro fluidic [15] and cell imaging [20]. However, nearly all the reported sensing schemes adopt the detecting area on the surface of guided layer, and the enhanced electromagnetic field is located inside or on the corner of the guided layer [8–20]. In the past, researchers were emphasized on confining the guided layer thin enough to suppress the arising of higher-order mode [21–23]. Even high value of enhanced electrical field value can be acquired, the distribution of the enhanced field is not good enough. Also, PCs have certain up limits in the field of sensing since a large fraction of the optical power is coupled into the guided layer instead of propagates in the evanescent field outside the physical boundary of the guided layer. By this way, the enhanced electrical field is separated from the analytes on the surface and cannot make a wholly contribution to the sensor. As the enhancement factor of evanescent field is exponentially decay on the above of PC surface [20,24], the sensing area of traditional PCs is very limited.

Meanwhile, microfluidic PC structures have been used for Reflective index sensing related area, like the detection of dissolved avidin concentrations on slotted photonic crystal cavities [25], measurement of the kinetic binding interaction of protein A with IgG molecules on polymer microfluidic channels [26], and microfluidic refractive index sensors [27] in the past few years. As far as we know, all these PC based microfluidics in the above references [24–27] are worked on the fundamental mode of resonance, in which the enhanced evanescent field will be mostly distributed on the edge of the grating angle or inside the guided layer, and cannot interact significantly with the detection sample. Nowadays, nanofluidic sensors, which can be used for biochemical, medical and life science detection, have been investigated worldwide [28]. Most of these nanofluidic sensors are fabricated as a single fluidic channel, and the analytes inside the channel need to be detected with aided tags, such as fluorescence [29], current [30]. To design a nanofluidic sensor that can test analytes with its own characteristics is of key importance.

---

* Corresponding author.
E-mail address: ypchen@mail.hust.edu.cn (Y. Chen).

http://dx.doi.org/10.1016/j.optcom.2016.07.019
0030-4018/

In this paper, a novel PC based nanofluidic sensor has been presented, which can work on the higher-order mode and has a detection area set inside the PC. To the best of our knowledge, there has been no publish to date of PC based nanofluidic sensor which is working on higher-order mode with liquid channel inside the PC structure. A well designed structure has been proposed, which is working on the 532 nm wavelength on resonance. The resonance peak induced by the higher-order mode is used to sense ambient RI (refractive index), instead of the fundamental mode, and the electric field distributes on the center of detection area while working in higher-order mode. The proposed PC based nanofluidic sensor possesses high sensitivity, compact size, and multi channels which can be used to detect different samples at the same time. This paper gives detailed method about how to design a PC sensor and optimize the related parameters to obtain the ideal structure. Based on FDTD simulation results, the superior performance of higher-order TE01 mode had been analyzed and demonstrated by simulation results. A brief way of how to fabricate this sensor was given. Also, the upcoming issues when passing from the theoretical part to the experiments were discussed. In the future, we will focus on fabricating and testing its performance with experiments.

2. Physical principle and device scheme

The physical phenomenon behind the narrowband reflection from PC has been described previously [31,32] as the periodic index differences enabling the exciting of guided mode resonance. The resonance wavelength occurs when the incident light satisfies the phase matching condition [33]:

$$k_0 n_c \sin\theta \pm m\left(\frac{2\pi}{\Lambda}\right) = \beta \tag{1}$$

where $k_0 = 2\pi/\lambda$ is the wave vector in free space, θ is the incident angle, n_c is the refractive index of the cladding area (in this structure, n_c is decided by the refractive index of Pyrex and liquid in nanofluidic channel), $m = 0, \pm 1...$ is the diffraction order, and $\beta = \frac{2\pi}{\lambda} n_{eff}$ is the propagation wave vector in the PC structure, and n_{eff} is the effective index.

The PC based nanofluidic sensor in this research has a Si3N4 based periodic structure built on the Pyrex substrate and covered by glass, while the nanofluidic channel is made by the gap between gratings. The grating period (Λ) and grating depth (d) of the sensor structure are depicted in Fig. 1. Since the gap between the Si3N4 based periodic structures will be used as nanofluidic channels, we plan to set it in a reasonable way, which means the size of the channel should be possible to fabricate with normal cleanroom equipment. For this PC based nanofluidic sensor, the detection of light is under normal incidence (θ=0) on the PC plane, and the targeted resonance wavelength will be 532 nm. Thus, θ=0, and we can rewrite the formula (1) as follows:

$$m\lambda = \Lambda n_{eff} \tag{2}$$

For a certain period, when there is a PWV according to the effective index changes resulting from ambient RI perturbation, we can get:

$$m\Delta\lambda = \Lambda\Delta n_{eff} \tag{3}$$

From (2) and (3), we can deduce that the sensitivity of PC based nanofluidic sensor is decided by the perturbation of effective index, which is mainly due to the interaction between the electrical field and the nanofluidic channels, as we can calculate from Eq. (4).

The resonance wave couples into the guided layer due to the perturbation of the grating structure. The ambient refractive index vary leads to redistribution of electric field and concomitant spectral changes of the reflected far fields which can be detected by a spectrometer. The effective index can be regard as the average of the refractive indices of the materials at resonance mode, and can be written as [34]:

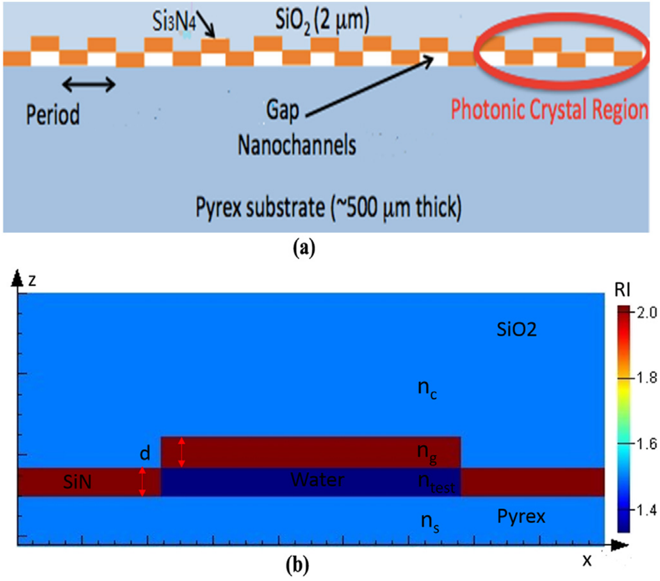

Fig. 1. PC based nanofluidic design comprised on a Pyrex substrate, a Si3N4 grating layer, and a SiO2 superstrate. (a) PC based nanofluidic sensor schematic diagram; (b) Parameters and refractive indexes (RI) of PC based nanofluidic sensor; d: grating depth, n_g: RI of Si3N4, n_{test}: RI of test analyte (e.g. water), n_s: RI of substrate Pyrex, n_c: RI of cladding layer, SiO2.

$$n_{eff}^2 = \frac{\int_{-\infty}^{\infty}\int_0^{\Lambda} \varepsilon(x, y)|E(x, y)|^2 d_x d_y}{\int_{-\infty}^{\infty}\int_0^{\Lambda} |E(x, y)|^2 d_x d_y} \tag{4}$$

where $\varepsilon(x, y)$ is the dielectric permittivity, and $E(x, y)$ is the electrical field intensity.

In order to improve the sensitivity of the sensor, the enhanced electrical field need to be confined mostly in the channel, where the interaction is exist.

3. Design method and results analysis

In this section, an analysis method for optimizing the electrical field enhancement within the channels in the sensor and predicting the absolute resonance wavelength at 532 nm have been proposed and discussed.

3.1. Design method

For a certain period, there is only fundamental mode when the grating depth is very thin. Whereas the higher-order mode occurs as the grating layer is thick enough. For any specific PC, there are two types of input parameters: structure-determined parameters and user-intent parameters [35]. The structure-determined parameter include grating depth d, refractive index of the cladding layer n_c, grating layer n_g, substrate n_s, and test sample area n_{test}, grating period Λ and fillfactor f which are determined by the structure of PC. The user-intent parameters include resonance wavelength value λ, incident angle θ, and polarization (TE, TM), which can be tuned by designer after the PC structure have been fabricated. In this paper, the structure-determined parameters were used to design the PC for PWV at 532 nm, and the user-intent