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Tunable photonic band gaps in a photonic crystal fiber filled with low index material

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The transmission spectrum of a photonic bandgap fiber filled with low index material is investigated. A simple analytical model is developed to predict the position and bandwidth of the band gap in the wavelength domain with respect to the refractive index. The wavelength of the band gap has a blue shift and the bandwidth of the band gap becomes narrow with the increasing of the refractive index of the filled material. The degree of shifting of the band gap increases with the reduction of air-filling fraction of the photonic bandgap fiber.

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1. Introduction

Photonic crystal fibers (PCF) are characterized by having a pattern of micrometer-sized air holes along the entire length of the fiber [1]. The most common names for addressing these fibers are index-guiding PCF and photonic bandgap (PBG) PCF, which also indicate their guiding mechanisms. The former mechanism is similar to a step index single mode fiber (SMF) by the total internal reflection in which the refractive index of the core is larger than that of the cladding. The latter guides the light in the low index core by the band gap effects of the cladding. Moreover, the transmission spectrum of the PBG fiber is characterized by having several transmission windows which are defined as band gaps, while index-guiding PCF does not.

The peculiar spectrum characteristic of the PBG fiber together with the ability for tuning the band gap may lead to the development of some potential devices such as tunable filters or dispersion compensators. Recently, much attention has been devoted to develop tunable PBG fiber devices by filling the holes of index-guiding PCF with high index material, i.e. n>1.45 [2-4]. Tunable photonic PBG fiber with high index oil in the air holes of a PCF was demonstrated by Bise et al. [2]. By changing the temperature, the positions of the transmission windows can thus be shifted. Recently, a thermo-optic fiber switch and tunable PBGs using thermo-optic tuning of the Liquid Crystals (LC) inside the holes of the PCF was presented [3]. The band gaps of the Liquid Crystal PCF can also be electrically tuned by placing it between the electrodes [4].

However, the spaces between the transmission windows are very narrow for the PBG fiber filled with high index material. Therefore, when the refractive index of the material decreases, the transmission windows become broader and overlapped [3]. This will greatly deteriorate the performance of the optical filter devices. This problem is able to be solved by filling the PBG fibers with low refractive index material. In the transmission spectrum of this kind of fiber, the spaces between the transmission windows are large enough so that the transmission windows will not overlap during the operation.

In this paper, the position and bandwidth of the primary band with respect to the change of refractive index of the low index material in the air holes of the PBG fiber are investigated. A simple analytical model is developed to understand this phenomenon.

2. Theory

Fig. 1 shows the cross section of a typical PBG fiber [5]. It consists of an air core which is surrounded by five rings of circular air holes. The circular air holes are arranged in a triangular lattice. The black region is for air holes, while the white region is for silica. The hole diameter and the distance between the adjacent holes (pitch) are d and Λ, respectively. The refractive indices of the circular holes and background material are n_a and n_b, respectively. The background material is assumed to be made of silica and it has the refractive index of 1.45.

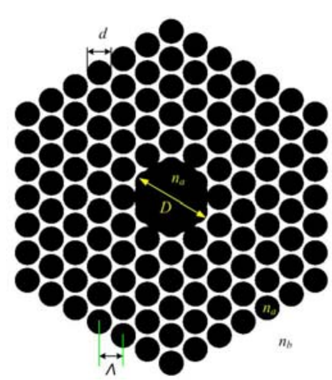

Fig. 1. PBG fiber with its air holes arranged in a triangular lattice described in [5]. Black regions represent air.

Two parameters of interests for the PBG fiber are the positions and bandwidths of the band gaps. These two parameters are functions of the geometry of the fiber and the index contrast between fiber materials, i.e., silica and low index material [2]. The modification of the refractive index of the low index material will change the positions and bandwidths of the band gaps simultaneously. However, there is no explicit expression to describe the relationship between the changes of the positions or bandwidths of the band gaps and the variation of the refractive index of the circular holes. It thus imposes the difficulties on the design and analysis of the performance of the tunable filters or chemical sensors by the use of PBG fibers.

To derive an explicit expression, a certain kind of approximation must be made in order to solve the Maxwell equation. The wavelength shift of the band gap is usually achieved by infusing the circular holes with polymer or optical liquids whose refractive index are able to be modified by temperature or other methods [2-4]. Moreover, most polymers or optical liquid have refractive indices larger than 1.33, and therefore the refractive index contrast between the circular holes and the background material is small. A weakly-guiding approximation or scalar approximation can thus be made [6]. After taking this scalar approximation, the Maxwell equation can be reduced into a scalar equation, i.e.

$$\nabla_t^2 \varphi = (\beta^2 - k_0^2 \varepsilon(x,y))\varphi \tag{1}$$

where $k_0=\omega/c=2\pi/\lambda$ is the wave vector, $\varepsilon(x,y)$ is the transverse dielectric constant profile, β is the propagation constant and φ denotes either E_x, E_y, E_z, H_x, H_y or H_z.

The transverse dielectric constant profile $\varepsilon(x,y)$ can be written as:

$$\varepsilon(x,y) = \varepsilon_b + (\varepsilon_a - \varepsilon_b) g(x,y) \tag{2}$$

where

$$g(x,y) = \begin{cases} 1 & \text{Air hole region} \\ 0 & \text{Silica region} \end{cases}$$

It is obvious that $g(x, y)$ is a normalized transverse dielectric constant profile, and therefore it is determined by the geometry of the fiber.

The propagation constant β can be written as

$$\beta^2 = k_0^2 n_{eff}^2 \tag{3}$$

where n_{eff} is the effective index of the fundamental core mode.

Substituting Eq.(2) and Eq.(3) into Eq.(1), the Maxwell equation can thus be written as

$$\nabla_t^2 \varphi = k_0^2 \left((n_{eff}^2 - n_b^2) - (n_a^2 - n_b^2) g(x,y) \right) \varphi \tag{4}$$

Eq.(4) is to be viewed as an eigenvalue equation for the unknown eigenvalue k_0 and eigenvector φ, with the effective index n_{eff} as a free parameter. For a given value of n_{eff}, the band gap is able to be evaluated by a plane wave method. Consequently, the band structure can be characterized as a function of n_{eff}.

Interestingly, if the core has the same material as the holes in the cladding, i.e., $n_{eff} \approx n_a$, Eq.(4) can be written in a more simple form:

$$\nabla_t^2 \varphi = k_0^2 (n_b^2 - n_a^2) \left(g(x,y) - 1 \right) \varphi \tag{5}$$

It is worth noting that the contribution of the material is only a scaling factor of k_0. The eigenvalues of Eq.(5) are determined by the function $g(x, y)$, i.e., the geometry of the fiber. Supposing A_{edge}, is the eigenvalue which determines the photonic band edge (PBE), the wavelength of the PBE (λ_{edge}) can be given by

$$k_0^2 (n_b^2 - n_a^2) = A_{edge}$$

$$\lambda = \left(\frac{2\pi}{\sqrt{A_{edge}}} \right) \cdot \sqrt{n_b^2 - n_a^2} = C \cdot \sqrt{n_b^2 - n_a^2} \tag{6}$$

where C is equal to $2\pi / \sqrt{A_{edge}}$. The first term C represents the waveguide contribution, which is determined by the geometry of the fiber. On the other hand, the second term is the material contribution. Therefore, the relationship between the wavelength shift and the variation of the refractive index within the holes is able to be evaluated in this explicit function.

In addition, the bandwidth of a transmission window can be also derived by subtracting two edges of the band gap. The bandwidth can hence be expressed as

$$\Delta\lambda_{edge} = (C_1 - C_2) \cdot \sqrt{n_b^2 - n_a^2} = W \cdot \sqrt{n_b^2 - n_a^2} \tag{7}$$

where C_1 and C_2 are the coefficients for the two edges of the band gap and W is equal to C_1-C_2.

3. Simulation results and discussion

Since the wavelengths of the PBEs are functions of the refractive index of the filled material (n_a), the position of the transmission window can be shifted by changing n_a. Experimentally this can be realized by using materials whose refractive indices are temperature dependent [2-4]. The tunability can thus be achieved by placing a micro-heater on a surface of PBG fiber filled with thermally tunable material such as a low index liquid. The temperature coefficient (the change in refractive index for a given change in temperature) for liquids is always negative, almost always much larger than for solids, and almost always -0.0004 RIU/°C (refractive index units per degree centigrade) [7].

Inasmuch the tunability is dependent on wavelength shift of the PBE with respect to the change of refractive index, in the following, the variation of the primary PBG region with respect to the modification of the refractive index (n_a) and air-filling fraction (f) will be presented. The air-filling fraction is the total hole volume fraction which is equal to $\pi d^2 / (2\sqrt{3}\Lambda^2)$. The knowledge of the primary band gap was obtained by a full-vector plane wave expansion (PWE) method in which primitive basis vectors were used, and the number of plane waves was set to be 256×256 [8]. After the position of the band gap was obtained, the corresponding transmission spectrum was evaluated by a standard beam propagation method (BPM) method [9]. This was done by launching a Gaussian beam in the center of the core with the width equal to that of the core and the propagation length was 2^{11} µm. The analytical results were evaluated by Eq.(6). It should be noted that although the low index material such as liquid or polymer are typically lossy, this waveguide is still able to be used as filter since only a short piece of fiber is required for this application. Consequently, in the following simulation, the lossy properties will be neglected. In addition, the higher order PBGs will not be taken into account due to their narrow bandwidths and far away from the primary band.

Fig. 2 shows the transmission window, i.e. PBG, for the fiber with air fraction *f* of 0.7 and water is filled into the circular holes. The refractive index of water is 1.33. The distance between the adjacent holes (Λ) is chosen to be 3.6 µm in order to adjust the central wavelength of the transmission window around 1550 nm. The transmission window spans from 1.35 µm to 1.65 µm which represents the primary band gap.

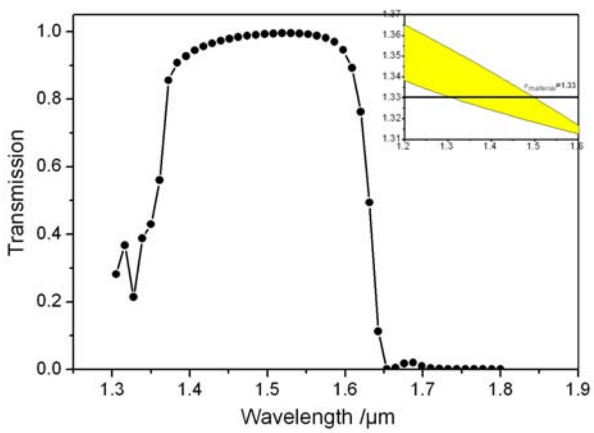

Fig. 2. Transmission spectrum for a PBG fiber filled with water. Inset figure: Shaded regions are gap regions.

To evaluate the performance of the filter, the transmission spectra for different index profiles within the holes are shown in Fig. 3 (a). Taking the 3-dB transmission points in the rising edge and falling edge of the transmission window as a reference, the corresponding wavelength shifts of two edges of the transmission window are illustrated in Fig. 3 (b). It shows that the transmission window has a blue shift and the corresponding bandwidth shrinks with the increase of the refractive index. For the fiber which is shown in Fig. 1 with a pitch of 3.6 µm, the rising edge and falling edge of the transmission window shifts from 1355 nm to 563 nm and from 1630 nm to 677.7 nm, respectively, when the refractive index increases from 1.33 to 1.43. Given the air holes are filled with material with refractive index of 1.33 and temperature coefficient of -0.0004 RIU/°C, the tunability is able to be achieved to be 2.16 nm/°C for the rising edge and 2.6 nm/°C for the falling edge.

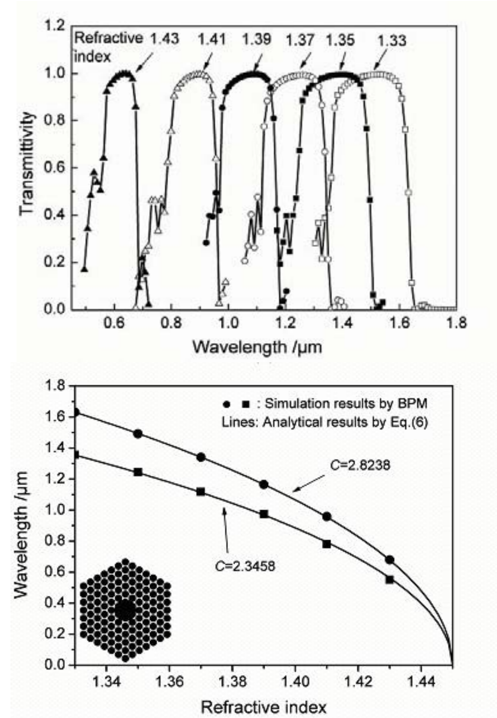

Fig. 3. (a) Transmission spectra for different index profiles within the circular holes. (b) Wavelength shifts of two edges of the transmission window.

Fig. 4 shows the variations of the band gaps with different air-filling fractions as the refractive index changes. For comparison, the pitches for the PBG fibers with three air-filling fractions are the same values which are 3.6 µm. It is clear from Fig. 4, the transmission window for the PBG fiber with less air-filling fraction has a larger wavelength shift. Accordingly, the variation of temperature will induce larger wavelength shift for the PBG fiber with less air-filling fraction.

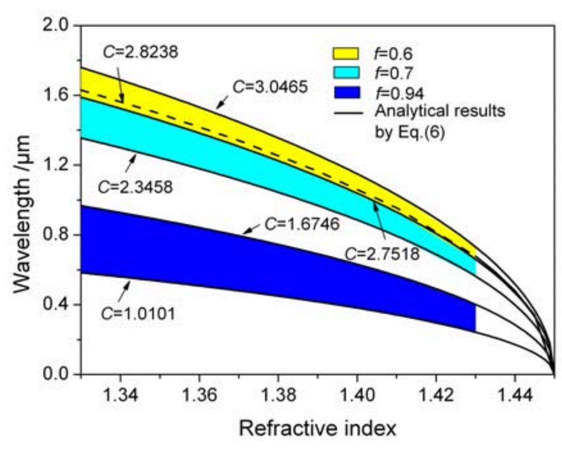

Fig. 4. Variations of the band gaps with different air-filling fractions as the refractive index changes.

4. Conclusion

In conclusion, analytical approaches were developed for understanding the spectral properties of the PBG fiber with low refractive index material filled in the air hole regions. A simple formula was derived for accurate prediction of the relationship between the positions and bandwidths of the band gaps with respect to the refractive index of the inclusion material. By infusing thermally tunable material such as a low index liquid, the transmission window is able to be adjusted in a controlled and predictable way providing a basis for novel photonic devices.

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