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PHOTONIC CRYSTAL FIBER MODAL INTERFEROMETER FOR REFRACTIVE INDEX SENSING

We present a modification of core-cladding intermodal interferometer for refractive index sensing. Its structure consists of double cladding photonic crystal fiber (PCF) as a sensing element. First cladding allows fundamental mode propagation only. Second cladding consists of ring of holes with the average refractive index higher than the basic material of the fiber and it is situated close to interface fiber-external environments. So the cladding mode is confined in the ring of holes and its evanescent field extends to external environment. Advantages of this arrangement against core - cladding interferometers are higher sensitivity and, by suitable choice of refractive index of second cladding holes, the possibility to investigate the external refractive index in the region where phase constants of interfering modes shows an extreme (equalization wavelength) in the spectral region.

Keywords: Intermodal interference, optical fiber sensor, photonic crystal fiber, refractive index sensing.

1. Introduction

There has been great interest in optical sensors in recent days. A large attention is given to sensors based on Bragg gratings and periodical structures made inside the fiber [1], or other optical materials [2] but also the fiber sensors based on intermodal interference [3] has the potential. For construction of these sensors optical fibers with different geometrical and propagation parameters can be used [4, 5]. Especially interesting fibers for sensor construction based on intermodal interference are those with photonic structure [6] due to the unique guiding mechanisms. In photonic crystal fibers (PCFs) can be observed the interference of two core modes [7], or the interference of two modes spreading in different areas of fiber. First approach is not very suitable for sensor construction due to critical launching and polarization conditions. In contrast, sensors based on second approach enjoy greater popularity in the sensor community. Sensors based on interference of modes spreading in different cores (two cores and more cores fibers) [8] have low temperature dependence due to the same material and are suitable for measurement of parameters as a curvature, a strain and a pressure. But usually, these structures are not suitable for measurement of external refractive index. In contrast, the interference of core and cladding mode is suitable, except the above-mentioned parameters, to measure the refractive index [9].

Here, we propose a modification of core-cladding intermodal interferometer for refractive index sensing based on double cladding photonic crystal fiber as a sensing element. First cladding allows fundamental mode propagation only (endlessly single mode propagation). Second cladding consists of ring of holes located close to the cladding-surroundings interface. Since the average refractive index of the ring is higher than basic material of the fiber the

“cladding” mode propagates through the holes. This makes the transmission of the sensing element dependent on the refractive index of the external environment. By suitable choice of refractive index of second cladding holes, it is possible to investigate the external refractive index in the region where phase constants of interfering modes show an extreme [10] – center of interference (equalization wavelength) in spectral region. The sensing element can operate at different wavelengths as well as coated with thick films made of variable index materials.

2. Intermodal interference

Light in an optical fiber propagates by means of modes of electromagnetic fields. A particular mode propagates with phase constant β which depends on parameters of an optical fiber surroundings and can be different for particular modes. The phase constants difference allows observing intermodal interference under special conditions.

The signal s generated by a quadratic detector at the end of the fiber (length of z) can be expressed as

$$s(z) = \int_S c(x,y) \cdot \sum_i \psi_i(x,y,z) \cdot \sum_i \psi_i^*(x,y,z) dx dy \quad (1)$$

where $c(x,y)$ is the detector sensitivity, $\psi_i(x,y,z)$ are the functions describing the propagating modes and are equal to $\psi_{i,0}(x,y) \cdot \exp(j\beta_i z)$, where $\psi_{i,0}$ are the modal functions, β_i are the phase constants of particular modes, x and y are the coordinates perpendicular to the direction of the propagation, S is area on which the modal function is nonzero and $*$ denotes complex conjugation.

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Expression (1) can be rewritten as

$$s(z) = \int_S c(x,y) \cdot \sum_k \psi_{k,0}(x,y) \cdot \psi_{k,0}^*(x,y) \cdot dx dy + \int_S c(x,y) \cdot \sum_{l \neq k} \psi_{l,0}(x,y) \cdot \psi_{k,0}^*(x,y) \cdot \exp(j\beta_{lk}z) \cdot dx dy \quad (2)$$

$\Delta\beta_{lk} = \beta_l - \beta_k$ is phase constants difference. The first integral of Eq. 2 represents the sum of particular mode intensities. The second integral of Eq. 2 is the interference term. It is clear that while the sensitivity c does not depend on coordinates its value is zero, because

$$\int_S \psi_{l,0}(x,y) \cdot \psi_{k,0}^*(x,y) dx dy = 0 \quad \text{for } l \neq k \quad (3)$$

It means that the intermodal interference can be observed only when the detector sensitivity is not uniform or when the eigenfunctions are transformed into non-orthogonal functions.

We let $\phi = \Delta\beta z$ be the total phase difference accumulated along the intermodal interferometer.

While an external perturbation is imposed on the sensing element phase changes by the amount of $d\phi$. The physical quantities (temperature, strain, pressure and refractive index n of surrounding medium) can lead to phase changes.

The resulting phase change depending on the refractive index of surrounding medium can be written as [11]

$$d\phi = \frac{2\pi}{T_n} dn \quad (4)$$

where T_n is the quantity of refractive index that introduces a 2π phase change. So, the smaller the T_n , the greater the sensitivity.

3. Methodology

The proposed structure of double cladding photonic crystal fiber is shown in Fig. 1.

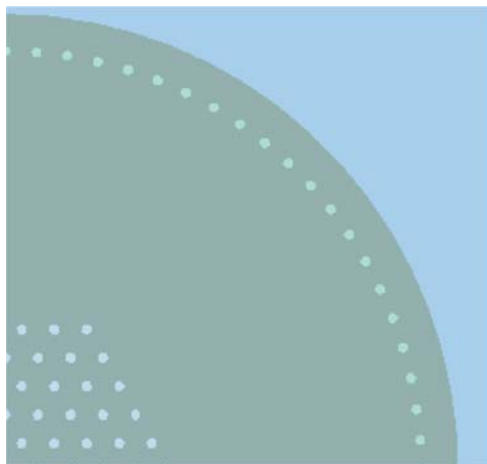


Fig. 1. The double cladding structure of PCF in quadrant $(0, \pi/2)$

Diameter of core is $9 \mu\text{m}$, the first holey region diameter is $65 \mu\text{m}$ and the second cladding, consisting of ring of holes, is located close to the cladding-surroundings interface. First cladding holes are filled by air with refractive index 1. Only one mode is propagated by the core of this structure. Refractive index of second cladding holes is 1.4602. So the average refractive index of the ring is higher than basic material and light (or cladding mode) is propagated through the ring (Fig. 3). Since the ring is close to cladding-surrounding interface the change of refractive index of surrounding will change the phase constant of mode propagation through the ring and thus it changes the character of modal interference.

To calculate modes in PCFs one needs to use numerical methods because of the complexity of the structure in PCFs. There have been several numerical methods invented throughout the time period of PCFs and even before. Some of them solve the wave equation and others solve directly the Maxwell equations without any assumptions for dielectrics. Although these methods differ they have one feature in common – they all use spatial mesh which discretizes simulated structure or simulation area into a finite set of points. Naturally, methods for discretization also differ and each is suitable for particular problem. The most known is the Finite Element Method (FEM) which discretizes the structure based on its complexity (Fig. 2a). From the user's view of point it is possible to setup the number of calculated points per domain. Second most used method for creating mesh is regular mesh with equal differences between neighboring points. This type of mesh does not depend on the shape of structure and usually has option of override mesh over complex regions (Fig. 2b).

One of the approaches of solving electromagnetic problems is Finite Difference Time Domain (FDTD), based on Yee algorithm (5). The mathematical relationship of the electromagnetic fields radiated by time-dependent current or charge densities is governed by Maxwell's equations. These are discretized using central difference approximations to the space and time partial derivatives. The resulting finite-difference equations are solved. So we simplify the vectorial equation taking just one component and rewrite it to discrete form taking the central difference approximations for both temporal and spatial derivatives [11]

$$\frac{E_x^{n+1/2}(k) - E_x^{n-1/2}(k)}{\Delta t} = -\frac{1}{\epsilon_0} \frac{H_y^n(k+1/2) - H_y^n(k-1/2)}{\Delta x} \quad (5)$$

$$\frac{H_y^{n+1}(k+1/2) - H_y^n(k-1/2)}{\Delta t} = \frac{1}{\mu_0} \frac{E_x^{n+1/2}(k) - E_x^{n-1/2}(k)}{\Delta x}$$

We used FDTD method based commercially available software MODE solutions (Lumerical Inc.) to perform the simulation.

The whole process of simulation in this software environment consists of two main parts. First is the layout part for drawing the structure, setting the material properties (Sellmeier coefficients and experimental data in our case), setting mesh and definition of boundary condition (PML). The other part is the analysis, where the modal properties of the structure are calculated. In purpose of intermodal

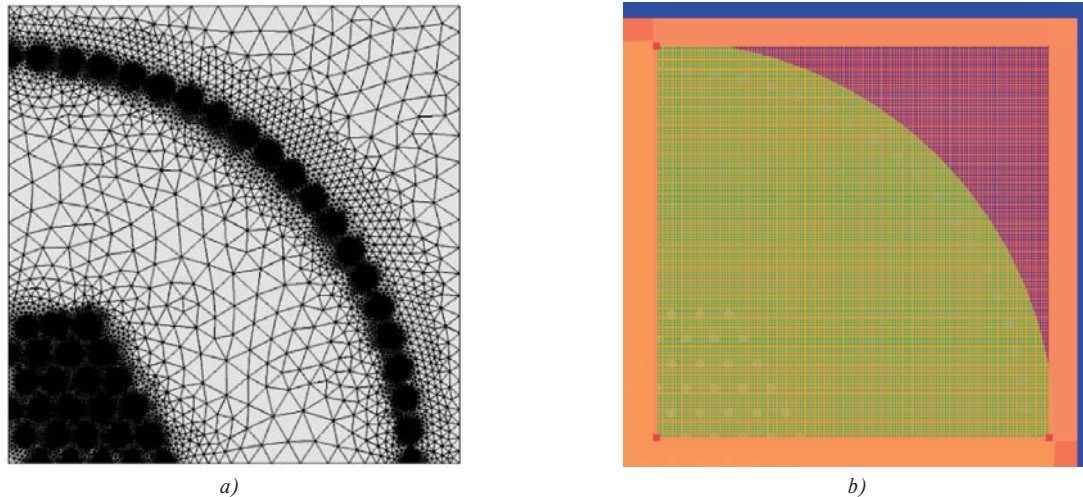


Fig. 2. Finite Element Method mesh (COMSOL 4.2.0), Regular mesh (MODE solutions 3.5a)

interference investigation it is necessary to choose suitable modes. In case of core mode it's quite simple, but cladding mode can be chosen only based on some physical parameter like polarization, overlap value etc. After that we are able to sweep the mode properties through the frequency or wavelength spectrum.

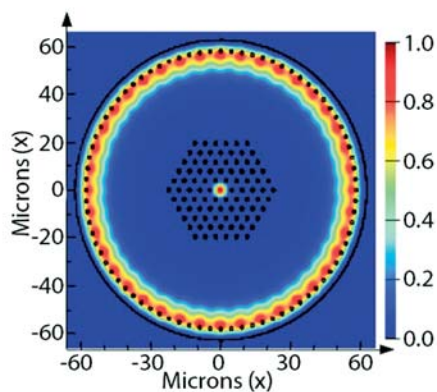


Fig. 3. Power flow distribution in linear scale of core (fundamental) and selected cladding mode for wavelength 1600 nm

4. Results and discussion

Since the mode in the second cladding is guided in the waveguide that is formed by glass - air interface the change of surrounding refractive index will also change its phase constant. This causes a shift in the interference fringes. Immersing double cladding PCF into the water ($n = 1.317$), we created glass - water waveguide and we simulated the spectral response. Similarly, we replace the water for higher refractive index substance ($n = 1.367$). Comparison of spectral responses is shown in Fig. 4.

In the case of glass-air interface the extreme of phase constants difference appears at 952.12 nm (blue curve), for glass-water interface is the extreme at 941.06 nm (red) and for glass - substance interface at 935.64 nm (green). If we consider the length (1.8 cm) of double cladding PCF, the interference between these two modes could be interpreted in the form of interference terms (Fig. 5).

Equalization wavelength dependence on external refractive index changes is shown in Fig. 6. There is also drawn a prediction of the dependence.

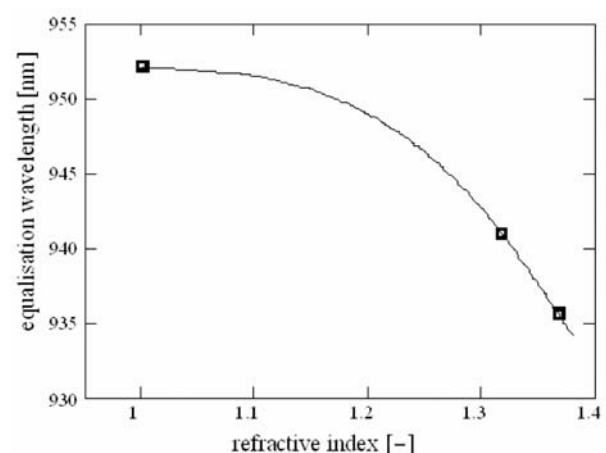


Fig. 6 Equalization wavelength dependence on external refractive index changes (points) and cubic spline interpolation

Similar to core-cladding interferometers the structure is insensitive (weakly sensitive) to changes of the refractive index of air [9]. But the structure is significantly more sensitive to changes of

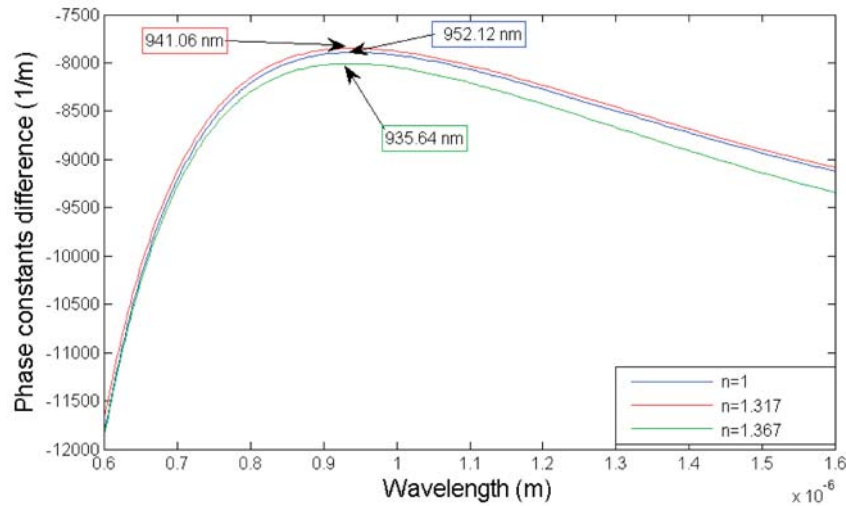


Fig. 4. Spectral Dependence of phase constants difference for different external refractive index

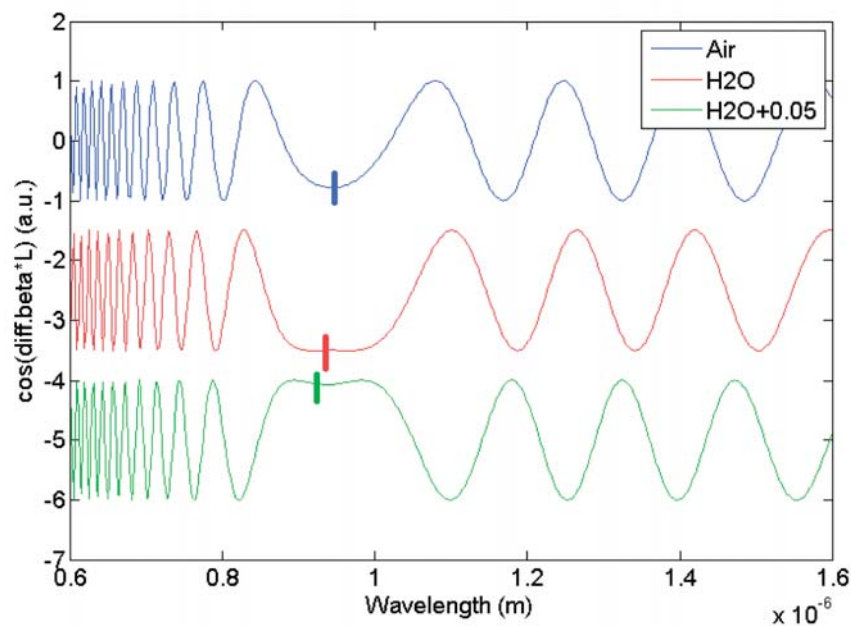


Fig. 5 Interference terms for glass-air(a), glass-water(b), glass-water+0.05(c) interface; curves are vertically shifted

refractive index of water (substances based on water). The equalization wavelength can be determined with accuracy better than 1 nm [12] so it is possible to determine the changes at 0.0095 refractive index units.

5. Conclusion

We propose a modification of core-cladding intermodal interferometer based on double cladding photonic crystal fiber as a sensing element. Main advantage of this structure is the possibility to

investigate the external refractive index in the region where phase constants of interfering modes show an extreme. Moreover, data obtained from the simulation shows that the sensor element can also be used to measure the refractive index of water-based substances where conventional core-cladding interferometers are insensitive.

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