Optik 125 (2014) 5936–5939

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Design of the novel steering-wheel micro-structured optical fibers sensor based on evanescent wave of terahertz wave band

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ARTICLE INFO

Article history:
Received 24 September 2013
Accepted 25 May 2014

Keywords:
Photonic crystal fiber
Evanescent wave
Terahertz
Sensitivity

ABSTRACT

In this paper, we present design of a hollow micro-structured photonic crystal fiber with novel steering-wheel pattern of noncircular large holes in cladding as platform for evanescent-field sensing. Based on simulation, confinement loss is less than 0.007 dB/m, and 72% of light intensity overlaps in noncircular large air holes is obtained when the incident wave frequency is 1 THz, and the nonlinear effects of the short-distance transmission are very small simultaneously. The critical value of confinement losses increases with the structure parameters. As for ultra-low loss and high sensitivity of the model, the novel steering-wheel structured fiber is well suited for evanescent-field sensing and detection of chemical and biological products.

1. Introduction

Photonic crystal fiber (PCF) is also termed micro-structured optical fiber (MOF) or holey fiber. Due to its unique structure features and novel optical characteristics, PCF has been increasingly explored for a large variety of applications ranging from communications to sensing [1–4]. PCF sensing platform based on evanescent field is of particular interest for chemical and biological sensing and detection [5–7]. The successful emergence of several PCF-fabrication techniques such as stack-and-draw [8], sol-gel casting [9], drilling [10], and extrusion [11], has enabled considerable design flexibility, which made it possible to obtain unique and intricate cladding microstructures in MOF with structural and optical properties tailored for sensing applications.

The design of steering-wheel microstructured optical fiber (SW-MOF) was proposed by Zhu and Du [12], the SW-MOF is used at infrared band, and has obtained confinement loss less than 0.7 dB/m. In recent years, the porous fiber has a widely application in the field of terahertz evanescent sensing [13], it provides a very flexible route toward THz wave guiding. Despite the popularity of evanescent-field sensing modality for fiber optic sensors, it continues to face the challenge of insufficient mode-field overlap with measurands and thus limits the sensitivity. This paper describes the design of novel steering-wheel microstructured optical fiber (novel SW-MOF) for evanescent-field based sensing. Optimal light intensity overlap in air hole is theoretically realized. The advantages of novel SW-MOF are as follows: (1) large light intensity overlap in noncircular holes are provided with high sensitivity; (2) low nonlinear effects and ultra-low confinement loss; (3) the structure has a good flexibility, because plastic is flexible comparing with silicon; (4) the structure has a great feasibility, the production process is simpler because the size of the model is greater than the general model.

Then, we analyze the influence change of novel SW-MOF structural parameters on the evanescent wave and simulate structural transmission characteristics of THz evanescent wave with finite element method. The background material is optical fiber of polymethyl-methacrylate (PMMA), because THz transmission losses are very small in plastic, and plastic which can be used in hash environments is flexible comparing with silicon.

2. Simulated model

2.1. Design of novel SW-MOF

The design strategy is based on an effective step-index model derived from classical fiber optics theory so that the traditional numerical approaches can be used for the description of our novel SW-MOF configuration. This Novel SW-MOF model is composed of the traditional porous optical fiber and SW-MOF [12,14]

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http://dx.doi.org/10.1016/j.ijleo.2014.05.045

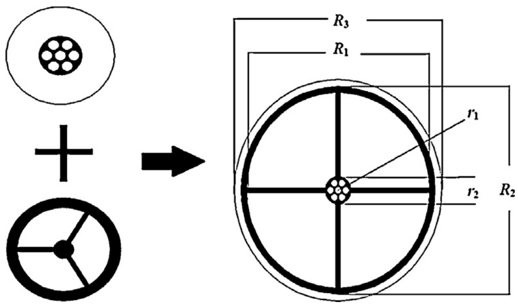

Fig. 1. Novel SW-MOF structure of design diagram and geometric parameters.

combination. Such design can achieve an air-filling fraction of about 93%, the minimum air holes diameter r_1 is 30 μm, hole pitch Λ is 35 μm, r_2 is 0.12 mm, R_1 is 0.866 mm, R_2 is 0.894 mm, R_3 is 0.954 mm, and web thickness d is ranging from 21 μm to 23 μm located in the model center parts, the novel SW-MOF configuration is shown in Fig. 1.

2.2. The principle of novel SW-MOF evanescent sensing

The principle of novel SW-MOF evanescent sensing is that the part of THz frequency radiation is absorbed through the reaction of being measured substance and evanescent in PCF, and then can analyze substance by detecting the THz radiation.

The novel SW-MOF is total internal reflection-type PCF which is characterized by guided-mode optical power concentrated at the center of the defects, while only a very small part of the optical energy (evanescent wave field) distributing in the surrounding noncircular large air holes. The evanescent wave is absorbed by substance medium in the air holes. Nonlinear coefficient, confinement loss, sensitivity and other parameters influence the performance of the novel SW-MOF model.

Nonlinear coefficient is an important parameter to judge the quality of the model. However, the effective mode field area (A_{eff}) impacts on nonlinear coefficient of the PCF, the relationship between the nonlinear coefficient and effective mode field area is [15]:

$$\gamma = \frac{2\pi n}{\lambda A_{eff}} \tag{1}$$

γ is nonlinear coefficient of the photonic crystal fiber, n is effective refractive index. Effective mode field area is inversely proportional to nonlinear coefficient, we make use of the effective mode field area to describe nonlinear effect, and the effective mode field area is defined as:

$$A_{eff} = \frac{\left[\iint |E(x,y)|^2 dxdy\right]^2}{\iint |E(x,y)|^4 dxdy} \tag{2}$$

$E(x, y)$ is the electric field distribution of mode field.

Fiber loss is an important parameter in photonic crystal fiber. The traditional fiber loss in the past few decades has been constantly reducing, we want to further reduce the traditional optical fiber loss has become increasingly difficult. In this paper, we analyze the confinement loss in the photonic crystal fiber by the finite element method. Confinement loss is defined as:

$$CL\left(\frac{dB}{m}\right) = \frac{20}{\ln 10} \times \frac{2\pi}{\lambda} \times Im(n_{eff}) \tag{3}$$

λ is the input wavelength; $\mathrm{Im}(n_{eff})$ is the imaginary part of the effective refractive index of the fundamental mode. According to Eq. (3), confinement loss depends on two variables, this two variables is input wavelength and the imaginary part of effective refractive index.

Sensitivity is an important parameter in the sensor based on evanescent wave too. Here we calculate the field distribution and analyze the evanescent field in photonic crystal fiber. In order to improve the sensitivity of the sensor, we further to optimize models. The numerically calculate formula of sensitivity is given by:

$$r_f = \frac{n_r}{n_e} f \tag{4}$$

n_r is refractive index of the filling substance, n_e is guide-mode effective refractive index, r_f is the relative sensitivity coefficient. As for novel SW-MOF model, f is the ratio defined as the optical power within the surrounding noncircular large air holes divides the total power, using the Poynting's theorem:

$$f = \frac{\int_{holes} (E_X H_Y - E_Y H_X) dxdy}{\int_{total} (E_X H_Y - E_Y H_X) dxdy} \tag{5}$$

Equation E_X, E_Y, H_X, H_Y express transverse electric and magnetic field model components. In this paper, the data are obtained by COMSOL Multiphysics 3.5.

2.3. Near-field image

The near-field image of novel SW-MOF is shown in Fig. 2(a). It is modeled using beam propagation method that allows analysis of the fundamental mode in core and its optical properties. The sensitivity of the model depends on power ratio of the input light and evanescent wave which is the part of the light leaked to the test substance region. Fig. 2(b) and (c) are near-field image of the traditional solid-core PCF and near-field image of the traditional porous optical fiber, respectively. Novel SW-MOF allows a guided mode to overlap with adjacent air holes more efficiently because sufficient surface area of core is exposed to the evanescent field in this paper; therefore, the sensitivity of this model is greater than traditional PCF.

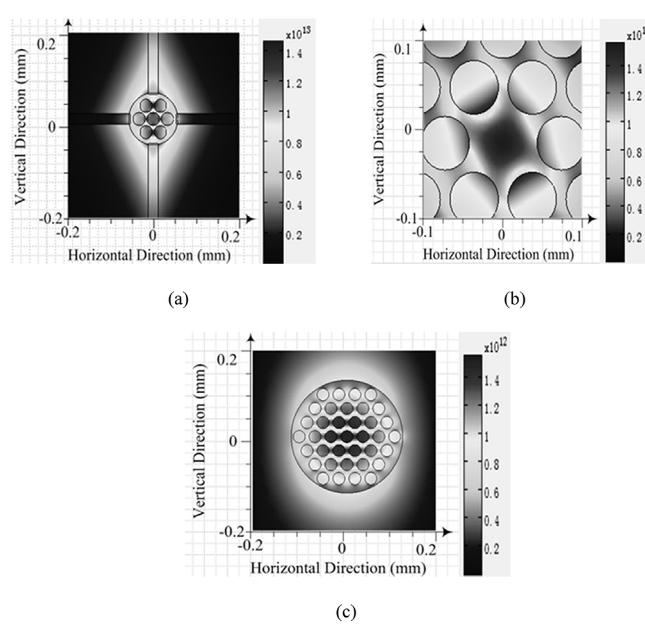

Fig. 2. (a) Near-field image of steering-wheel MOF air-hole cladding. (b) Near-field image of the traditional solid-core PCF. (c) Near-field image of the traditional porous optical fiber.