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Single-mode spiral shape fiber based liquid sensor with ultra-high sensitivity and ultra-low loss: Design and analysis

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Abstract

This paper represents a spiral photonic crystal fiber (S-PCF) based optical sensor which exhibits high relative sensitive as well as low confinement loss simultaneously. The proposed PCF contains ten arms as well as each arm consists of nine circular air holes that forms spiral shape and core is formatted with circular holes filled with ethanol. Various geometrical parameters including diameters and pitches of the suggested S-PCF are tuned with the most efficient structure applying the full vectorial finite element method (FEM). Overall outcomes satisfy O + E + S + C + L + U (range of 1.26−1.675 μm) electromagnetic (EM) bands. The relative sensitivities of about 72.95%, 74.55% and 75.14% with ultra-low confinement loss of 1.85×10^{-10} dB/m, 4.62×10^{-11} dB/m and 6.35×10^{-11} dB/m are gained at the 1.33 μm wavelength for water (n = 1.33), ethanol (n = 1.354) and benzene (n = 1.366) analytes respectively. In addition, effective area, non-linear coefficient and V-parameter are also examined. Finally, the inquiry procedure depicts that the proposed S-PCF is highly capable in not only sensing applications but also high data traffic transmission applications.

Keywords: Confinement loss; Fiber based liquid sensor; Nonlinearity; Relative sensitivity; Spiral shaped PCF

1. Introduction

PCF is ensured as a novel advancement in the fiber-optic communication system. It has some special features including endlessly single mode [1], highly birefringence [2], highly negative dispersion [3], lower beat length [4], highly numerical aperture [5], beam divergence [6], Marcuse spot size [7], mode field diameter [8], high nonlinearity [9], and large mode area [10] that distinguish PCF from the conventional optical fiber. PCFs are portioned in two major categories according to the optical characteristics of light. These are index guiding (IG) and photonic band gap

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(PBG) PCF. In the IG PCF, refractive index of the core region is greater than the cladding vicinity ($n_{core} > n_{cladding}$) and light rays have passed through the core territory by using total internal reflection (TIR) theory. Besides, the optical field can be passed through the PBG fiber core by obeying PBG mechanism and $n_{core} < n_{cladding}$. From the beginning era of PCFs, the different geometrical shapes have been proposed due to improving its performance. The researchers have suggested regular or irregular structures like spherical [11], D-shape [12], colloidal [13], helically twisted [14], fused tapered [15], hybrid [16,17], hollow core [18] and U-shape [19] design with the progress of fabrication technology. Various background material such as silica [20], Topaz [21], copper and graphene [22] are utilized to enhance the performance of the PCF. The dual [23], suspended [24], and As_2S_3 chalcogenide [25] type cores are also proposed for future PCF based research. As a result, PCFs are suitable for different practical discipline including super-continuum generation [26], nonlinear optics [27], high power technologies [28], and sensing purposes [29].

Some appealing features (like small, aberrantly sensitive, robust) that allow the capacity to monitor remotely and make PCF based sensors become more popular [30]. The IG PCF is considered more suitable for sensing applications rather than the PBG fiber because of its complicated production procedure [31]. The IG PCF is effective in sensing purpose for evanescent interaction which is occurring between guided EM light mode and gas or chemical [30,31]. The fluorescence based remote irradiation [32], temperature sensor [33], magnetic field sensor [34], refractive index (RI) sensor [30], humidity sensor [35], Raman scattering sensor [36], and hydrostatic pressure sensor [37] are main usable PCF based sensor. Another important feature of the PCF is large mode area. It is applicable for producing and propagating high optical powers without restrictions due to the onset of intensity-dependent nonlinear effects [10]. V-parameter is also regarded as one of the significant features of PCF which is used to calculate single or multimode characteristics of the fiber. The single mode fiber (SMF) is utilized in long distance communication whereas multimode fiber uses in short distance communication. The multimode fibers (MF) are contained large core diameter which distinguishes it from the SMF. This property is responsible for high numerical aperture that increases light gathering capabilities of a fiber [5,38].

Researchers have contributed much effort due to enhancing chemical sensing capabilities of the PCF. In the year of 2000 [39], Lee and Asher proposed a PCF based chemical sensor that detected the pH and ionic strength. Knight et al. [10] suggested a PCF that exhibited large mode area. In the article [40], it had been reported an octagonal PCF and gained relative sensitivity of about 23.05% with low confinement loss of 5.74×10^{-6} dB/m at $\lambda = 1.33$ µm. But the obtained relative sensitivity seems very low at the earlier stage of 2016. Asauzzaman et al. [41] suggested a micro structured hybrid PCF for chemical sensing application which revealed high sensitivity, low confinement loss with high birefringence. The author's gained high sensitivity but the proposed structure was hybrid. That's why, they will face fabrication difficulties. In 2017, Paul et al. [29] proposed a folded cladding porous shaped PCF and achieved high sensitivity of about 64.19% and the confinement loss of 2.07×10^{-5} dB/m at $\lambda = 1.48$ µm for ethanol ($n = 1.354$) analytes. But the confinement loss was not improved compared to previous articles.

In this paper, we have reported a micro structured S-PCF for liquid sensing applications. The proposed structure exhibits high relative of about 74.55% and low confinement loss of 4.62×10^{-11} dB/mat 1.33 µm wavelength. By comparing with the previous research articles [29,41], our suggested PCF has shown 1.16 and 1.52 times excellent relative sensitivity respectively. For this reason, it ensures great development in sensing applications.

2. Geometrical structure of the proposed S-PCF

The proposed PCF contains a cluster of circular air holes in the core region which are formed into a microstructure shape [42] and cladding is formed with spiral shape which also contains circular air holes. Spiral technique has great attention due to their excellent modal confinement properties compared to conventional hexagonal PCFs [43]. In article [44], it was represented that the diameters of air holes located at innermost ring are responsible for high sensitivity as well as the diameters of outermost rings are accountable for lower confinement loss. Spiral symmetry consists of ten spiral arms, where each arm consists of nine circular air holes. The center to center distance between the two adjacent holes is called the pitch (Λ). For flexibility of the design Λ is chosen as $r_0 = \Lambda$ where r_0 is a distance of the first air hole in each spiral ring and Λ is the pitch of cladding. Throughout the investigations, the value of Λ is defined as $0.68{*}D_{core}$, where D_{core} is the core diameter. The diameter of air-hole at first three rings is defined as $d_1 = 0.58{*}\Lambda$

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