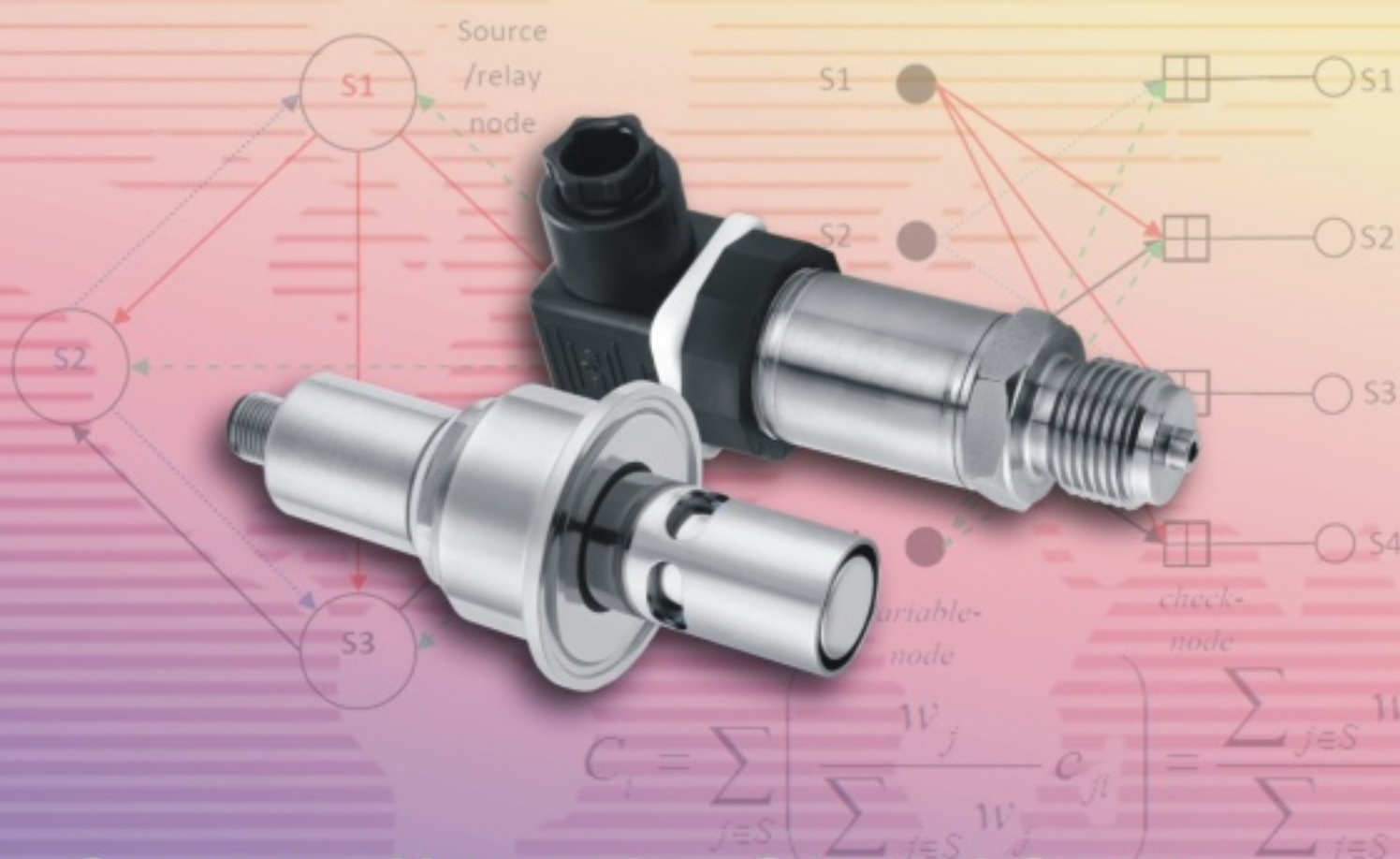


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Editor-in-Chief
Sergey Y. YURISH



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Contents

Volume 20
Special Issue
April 2013

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Research Articles

Application of Partial Least Squares Regression to Static Magnetic Grid Displacement Sensor <i>Qiao Shuang</i>	1
A Fast Responsive Refractometer Based on the Side-opened, Dual-core Photonic Crystal Fiber <i>Jiang Jianhu, Jiao Wentan, Song Lijun</i>	6
Code-Folding Scheme for Energy Efficient Cooperative Communications in Wireless Sensor Networks <i>Zhenbang Wang, Zhenyong Wang, Xuemai Gu</i>	12
A New Missing Values Estimation Algorithm in Wireless Sensor Networks Based on Convolution <i>Feng Liu</i>	21
Heterogeneous Network Convergence with Artificial Mapping for Cognitive Radio Networks <i>Hang Qin, Jun Su, Zhengbing Hu</i>	27
An Improved Phase-Coherent Algorithm for High Dynamic Doppler Simulation in Navigation Simulator <i>Qi Wei, Guo Junhai, Liu Guangjun, Luo Haiying, Wang Jing</i>	37
Implementation of Closed Loop Control System of FOG Based on FPGA <i>Q. D. Sun, Z. H. Zhu and B. P. Larouche</i>	46
Decentralized Robust Control for Nonlinear Interconnected Systems Based on T-S Fuzzy Bilinear Model <i>Zhang Guo and Zhao Yanhua</i>	53
The Formation of the Local Gravitational Model Based on Point-mass Method <i>Wang Jian-Qiang, Zhao Guo-Qiang, Yu Zhi-Qi</i>	64
Sliding Mode Tracking Control of Manipulator Based on the Improved Reaching Law <i>Wei-Na Zhai, Yue-Wang Ge, Shu-Zhong Song, Yan Wang</i>	69
The Study of Elderly Informational Education under “Cloud Computing” <i>Fan ChangXing</i>	79

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A Fast Responsive Refractometer Based on the Side-Opened, Dual-Core Photonic Crystal Fiber

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Abstract: For enhancing the sensitivity properties and accelerating the responsive characteristics at the same time, a novel refractometer based on a side-opened, dual-core photonic crystal fiber and dual-beam coupling detecting mechanism is proposed and analyzed here. The improvement is replacing a part of air holes of conventional dual-core photonic crystal fiber by one large circular hole, while the lateral segment of this large circular hole is supposed to be side opened. This side-opened fiber configuration makes fast responsive characteristics by allowing fluidic target approaching one of the fiber cores laterally and quickly. The dual-beam coupling mechanism ensures a relative higher optical sensitivity. Numerical simulation results show that a sensitivity of 3.8e-5RIU could be achievable, which reflects its potential value on high sensitive and fast responsive detection applications. Besides, the relation of the optical sensitivity and the dynamic detected index range on this novel dual core photonic crystal fiber structure, optical mode polarization and the transmitting waveband is also analyzed. *Copyright © 2013 IFSA.*

Keywords: Dual core photonic crystal fiber, Fiber refractometer, Side opened, Dual beam coupling detection.

1. Introduction

Fiber based refractometers have many advantages, such as high integration, high sensitivity, easy to make and low cost [1, 2]. One important kind of fiber refractometer is based on dual core fiber and interference/coupling detecting mechanism, which plus the advantage of ultra-high optical sensitivity characteristics due to the differential intensity detection or differential coherent detection mechanism [3-6]. Currently, many kinds of dual-core fiber based refractometers have been proposed, such as the dual core photonic bandgap fiber (PBGF)/photonic crystal fiber (PCF) [7], the dual core fiber/PCF grating [8] and the dual core total internal reflection(TIR) fiber/PCF [9,10]. Wu Yuan studied the characteristics of a refractometer scheme based on a solid twin-core PBGF with one fluid-filled-hole centered between the two cores [7]. By detecting the

variation of transmittance intensity at a fixed wavelength, a detection limit magnitude of 10-6RIU and a dynamic detected index range of 0.01RIU could be feasibly. But, its optical characteristic is originated from the phase matching of dissimilar waveguides, consequently it was only useful at a narrow detected index range. For broadening the detected fluidic index range, optical refractometers based on the fiber grating [8] and TIR PCF [9-11] are good ideas. The dual core fiber grating mechanism has the capability of decoupling all the parameters affecting the measurement and obtains precise measurements of the interested parameters. In TIR-typed PCF configuration, there exists an exponential dependence of core-core coupling on specific refractive index range of the detected analyte, which ensures a large detecting range and high sensitivity simultaneously. Besides, selective-filling the photonic crystal fiber with detected fluidic analyte could also increase the

optical sensitivity by approximately 1 magnitude order [8].

Besides, due to the close hole characteristics of conventional photonic crystal fiber, their optical responsive characteristics are restricted by the slow filling speed of detected fluid analytes. A feasible method is side opening the photonic crystal fiber by laser drilling, side polishing or chemical etching methods. Another way is drawing the side-opened fiber straightly during the fiber drawing process [12-14].

Inspired by upper progresses, here a novel fiber refractometer which combines the merits of dual core fiber and side opening characteristics is proposed here. The improvement is replacing a part of air holes by one large circular hole, while the lateral segment of this large hole could be side opened by side polishing method. Thus the detected fluid could fill into the large circular hole, which is the sensing area laterally and quickly. So the fast responsive characteristics could be attainable. For enhancing the optical sensitivity at the same time, the detecting mechanism based on the dual core coupling mechanism is utilized here. Moreover, the key parameters such as core diameter, hole size and pitch, transmitting wavelength are optimized for sensitivity enhancement. We show that by choosing appropriate fiber parameters, the fiber sensor could own a high optical sensitivity and a wide detected range at the same time.

The analysis is arranged as follows: In section 2, the configuration of the proposed fiber refractometer is revealed, the function of dual core coupling mechanism is deduced here too; In section 3, a detailed analysis of the characteristics of the proposed configuration is given, while the influence of fiber core size, air hole pitch and diameter, large circular hole parameters on refractometer sensing characteristics are studied; While in section 4, a summary of this configuration is proposed, its potential value on fast responsive, high sensitive fluid index sensing is also forecasted.

2. Configuration of the Proposed Fiber Refractometer

The cross section of the proposed dual core photonic crystal fiber refractometer structure is schematically depicted in Fig. 1. The base material of this proposed configuration is supposed as silica. In Fig. 1, two core of solid silica material is embedded into fiber cladding of array air holes for coupling. For fluidic refractive index sensing operation, the fiber size is designed to operate at fundamental mode. A part of the air holes is replaced by one large circular hole, while the lateral segment of this large circular hole could be side opened by side polishing method. Thus the detected fluid could fill into the large hole region (the sensing area) quickly. The silica core radius R , the air hole radius R_{air} , the large circular

hole radius R_{hole} and the air hole pitch Λ could be adjusted easily during the fabrication process for sensitivity enhancement by changing the optical energy distribution over the sensing region. The fiber cladding diameter is supposed of $125 \mu\text{m}$, which is easy for connecting with conventional single mode/multimode fiber. The distance between the dual cores is properly selected for considering a trading-off between the possibility of illuminating the dual cores using a standard single mode fiber beam source. This fiber mode distribution is simulated by the commercially available finite-element software (COMSOL multiphysics 4.3) [15, 16] between 1550 nm and 950 nm respectively. The refractive index of the silica n_{SiO_2} is the same as those in ref [17]. The refractive index n_{analyte} of the fluidic analyte is from 1.333 to 1.393 .

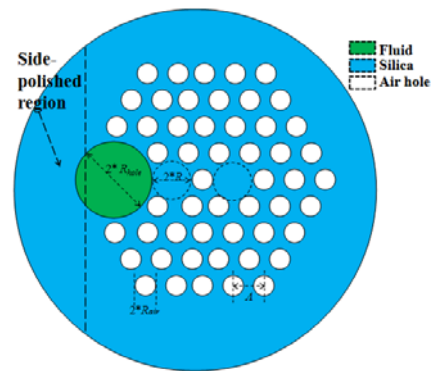


Fig. 1. Cross section of the proposed dual core photonic crystal fiber refractometer.

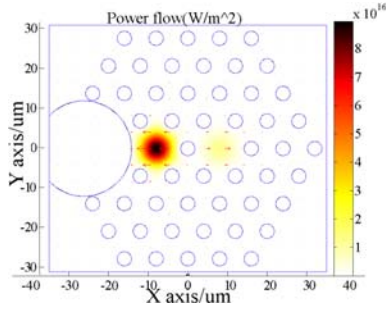
Fig. 2 shows the mode field intensity distribution of each polarization at 1550 nm transmitting wavelength in the dual core fiber refractometer with an R of $6 \mu\text{m}$, R_{hole} of $12 \mu\text{m}$, R_{air} of $1.8 \mu\text{m}$ and pitch of $8 \mu\text{m}$ when n_{analyte} equals to 1.333 . As seen in Fig. 2, there are two fundamental modes in each core region. The left core is close to the analyte, thus the influence of analyte index on their mode effective index is stronger than that of right core region. Since the detection mechanism is based on the mode coupling of the dual-modes of one polarization, we can deduce the sensing sensitivity characteristics based on the following functions.

For a balanced coupler, the proportion of the launched power coupled to the other core in a device of length is [19]

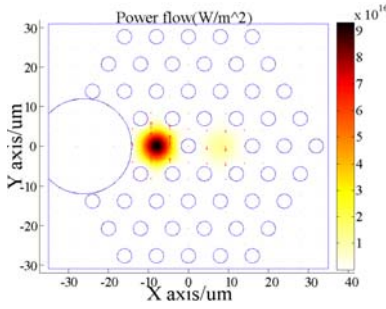
$$T_{21} = \frac{P_2(L)}{P_1(0)} = \sin^2(\theta/2), \quad (1)$$

where θ is the phase difference between the two fundamental modes, defined by

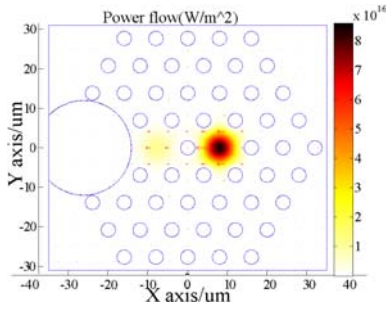
$$\theta = k \cdot L \cdot |n_{left} - n_{right}| = k \cdot L \cdot \Delta_{neff}(\lambda, n_a), \quad (2)$$



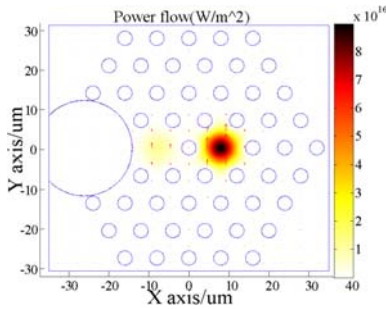
(a) TE mode of left core.



(b) TM mode of left core.



(c) TE mode of right core.



(d) TM mode of right core.

Fig. 2. Plot of intensity distribution of TE and TM polarizations at $\lambda=1550$ nm ($R=6 \mu\text{m}$, $R_{air}=1.8 \mu\text{m}$, $R_{hole}=12 \mu\text{m}$, $A=8 \mu\text{m}$, $n_{analyte}=1.333$)

In function (1) and (2), L is the length of the coupler, $\kappa=2\pi/\lambda$ is the free space propagation constant, λ is the transmitting wavelength, and n_{left} and n_{right} are the effective indices of the fundamental modes respectively, and $\Delta n_{eff}=n_{left}-n_{right}$. The coupling length L is defined as the fiber length to which the optical input has transferred completely from one core to the other core, so

$$L_c = \lambda / (2 \cdot \Delta n_{eff}(\lambda, n_a)), \quad (3)$$

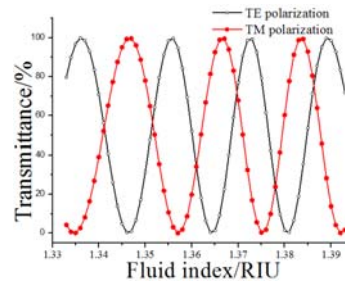
Here, the coupling length is proportional to the coupling coefficient of dual cores inversely, and varies with confinement of the core modes and separation between the cores rapidly, and in the dual-core photonic crystal fiber will also depend upon the refractive index of the fluidic analyte n_a .

The optical sensitivity of the dual-core photonic crystal fiber is simulated by coupled mode theory (CMT) and the finite element method (FEM) software COMSOL multphysics [14, 15]. For optimizing the optical sensitivity, the sensor must be biased to operate at 50 % transmittance, e.g. with $\theta=180$ degree or $L=L_c/2$. In practice this condition could be achieved by fabricating the device length to be an odd number of half-coupling lengths, or by temperature or wavelength tuning. Thus, under that condition, the sensitivity of the proposed side-opened dual core photonic crystal fiber can be given by

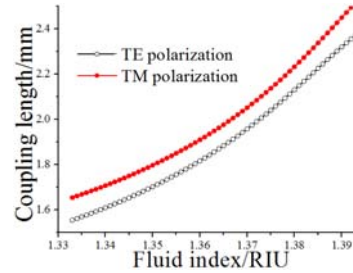
$$\frac{\partial T_{21}}{\partial n_a} = \pm(N+1) \cdot k \cdot L_c \frac{\partial(\Delta n_{eff})}{\partial(\Delta n_a)} = \pm(N+1) \cdot \frac{\pi}{\Delta n_{eff}} \frac{\partial(\Delta n_{eff})}{\partial(\Delta n_a)}, \quad (4)$$

which depends straightly on $\partial(\Delta n_{eff})/\partial(\Delta n_a)$ and scales with fiber refractometer length N .

Supposing the sensing length of fiber refractometer L is 3 cm, when light at 150 nm wavelength is coupled into one of the cores of the dual core photonic crystal fiber, the normalized transmittance of the opposite core after propagating through the sensing area is depicted in Fig. 3.



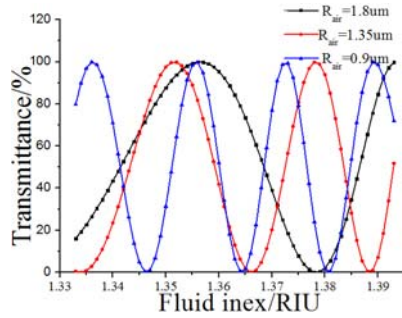
(a) Transmittance



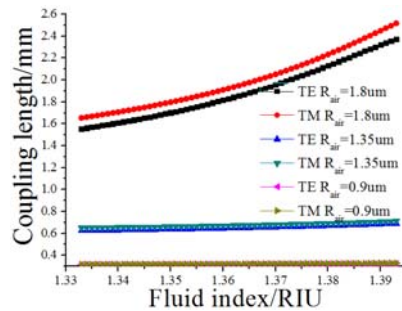
(b) Coupling length characteristic.

Fig. 3. Characteristics of transmittance and coupling length ($R=6 \mu\text{m}$, $R_{air}=1.8 \mu\text{m}$, $R_{hole}=12 \mu\text{m}$, $A=8 \mu\text{m}$, $\lambda=1550$ nm).

Consequently changes in refractive index may be determined from the variation in transmitted intensity at the fixed wavelength. Note that as the fluid refractive index and coupling increase, the transmittance passes through a series of nulls and peaks as the coupling length changes. The change of coupling length with analyte index is illustrated in Fig. 4.



(a) Transmittance.



(b) Coupling length characteristic.

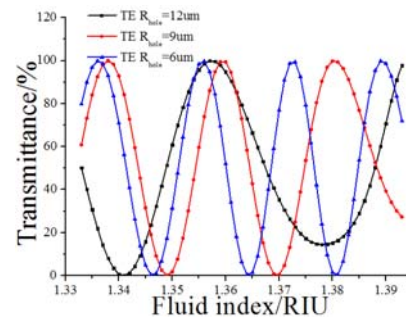
Fig. 4. Characteristics of transmittance and coupling length vs. air hole radius ($R=6 \mu\text{m}$, $R_{\text{hole}}=12 \mu\text{m}$, $A=8 \mu\text{m}$, $\lambda=1550 \text{ nm}$)

3. Numerical Simulation and Result Analysis

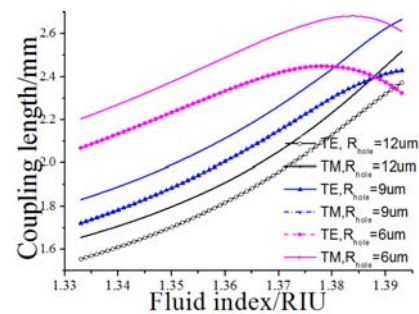
In this section, the influence of the fiber parameters and the transmitting wavelength on the fiber sensing characteristics is analyzed. First we analyze the impact of air hole radius on the optical sensitivity. Fig. 4(a) depicts the transmittance and coupling length characteristics versus analyte refractive index for different air hole radius. It shows that, with the rising of fluidic index of detected targets, the speed of transmittance variety from peaks to nulls increases, corresponding with an enhanced optical sensitivity. When the index reaches to 1.393RIU, the corresponding sensitivity of dual core photonic crystal fiber with air hole radius of $0.9 \mu\text{m}$ could come up to 2567 rad/RIU (deduced from function 5), the corresponding sensing resolution could reach up to $3.8\text{e-}5\text{RIU}$. It also seems that with the decrease of air hole radius, the transmittance variety becomes relative more quick, followed with

the enhanced sensitivity at the same detecting region. We attribute it to the less mode confinement ability and higher overlap towards to the sensing region (large circular hole) and the further greater influence on optical sensitivity with smaller air hole radius, which could be supported by Fig. 4 (b). As the coupling length is inversely proportional to the coupling coefficient between the two cores, and varies rapidly with confinement of the core modes and separation between the cores. It also shows that the difference of sensitivity characteristics of TM polarization and TE polarization are little. We attribute it to the little mode distribution difference of TM polarization and TM polarization towards the sensing region.

Then the impact of fluid-filled large circular radius on the optical sensitivity is analyzed. As shown in Fig. 5, the dual mode coupling length of each polarization ranges from 1.6 mm to 2.7 mm when the range of analyte refractive index is from 1.333 to 1.393. The sensitivity difference on different circular hole radius (from $12 \mu\text{m}$ to $6 \mu\text{m}$) seems significant. The reason is that a larger air hole diameter seems better for promoting the energy overlap towards to the circular hole region and enhancing the optical sensitivity. But it seems a better corresponding with special fluid index (near 1.385RIU when R_{hole} equals to $6 \mu\text{m}$). Thus, The varying dependence of coupling on fluidic refractive index, allows the fiber refractometer to be designed for maximum dynamic range or for maximum sensitivity to fluidic refractive index change according to the real demand.



(a) Transmittance



(b) Coupling length characteristic

Fig. 5. Characteristics of transmittance and coupling length vs. fluid-filled circular hole radius. ($R : R_{\text{air}} : R_{\text{air}}=6:12:1.8$, $\lambda=1550 \text{ nm}$).

Then, the coupling length characteristics versus core radius (when $R_{air}:R_{air}=6:12:1.8$) for selecting proper core radius in Fig. 6. It seems that with the decrease of core radius, the coupling length increases, which could benefit to the sensitivity enhancement later, but the coupling length come to maximum when the fluid index come to a special point. We think those results could also attributes to the difference of mode confinement ability and coupling length characteristics. As the smaller core radius could depress the ability of mode confinement at the same condition, more energy could distribute over the sensing region and its influence on effective mode index characteristic and coupling length are also enhanced then.

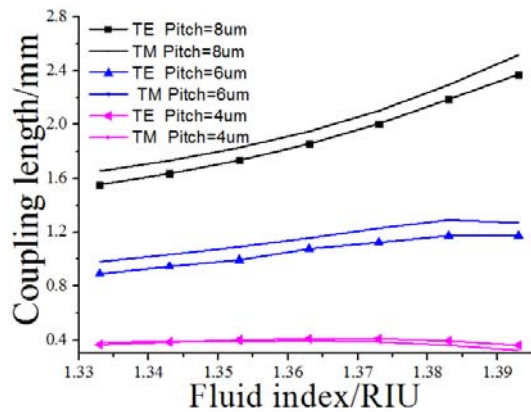


Fig. 6. Characteristics of coupling length vs. fluid-filled circular hole radius ($R=6 \mu\text{m}$, $R_{air}=1.8 \mu\text{m}$, $A=8 \mu\text{m}$, $\lambda=1550 \text{ nm}$).

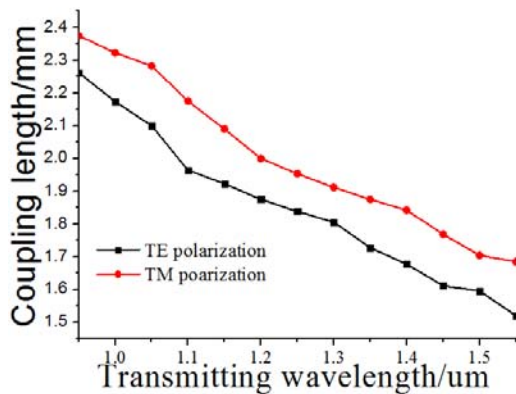


Fig. 7. Characteristics of coupling length vs. fluid-filled circular hole radius ($R=6 \mu\text{m}$, $R_{air}=1.8 \mu\text{m}$, $R_{hole}=12 \mu\text{m}$, $A=8 \mu\text{m}$, $n=1.333$)

Finally, Fig. 7 shows the coupling length characteristic vs. fluid refractive index from 950 nm to 1550 nm for selecting proper waveband. It seems In this dual core photonic crystal fiber refractometer, the coupling length decreases monotonically with increasing wavelength. We think it could also attributes to the difference of mode confinement

ability. As the longer wavelength could depress the ability of mode confinement at the same condition, more energy could distribute over the circular hole region (sensing area) and the influence on coupling characteristic are also enhanced then.

4. Conclusions

In this paper, we explore a novel refractometer by incorporating the side-opened structure into the dual-core photonic crystal fiber figuration. As the fluidic analyte could approach the side-opened circular hole laterally and directly, a fast molecule exchange speed and short sensing response time are feasible. Besides, the dual-core, dual mode fiber structure and the coupling detection mechanism also ensure a relative higher sensitivity which could reach up to 3.8e-5RIU. The detected range is also very wide. We think this novel configuration have potential value on fast responsive, high sensitive and wide detected range fluidic index detection applications.

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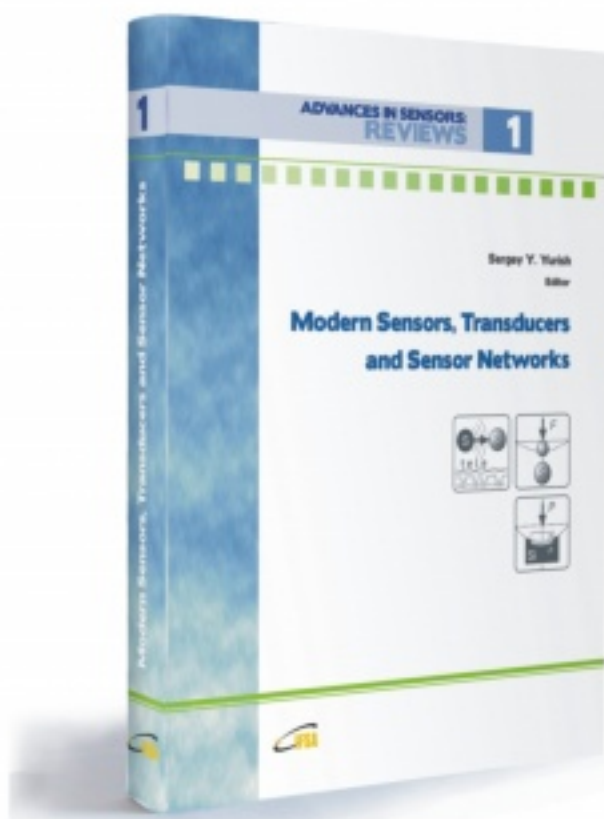
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