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HOLLOW-CORE PHOTONIC CRYSTAL FIBER REFRACTIVE INDEX SENSOR BASED ON MODAL INTERFERENCE

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ABSTRACT

A refractive index sensor based modal interference in hollow core photonic crystal fiber (HCPCF) is proposed and demonstrated. The sensor is realized by splicing both ends of a HCPCF section to single mode fiber (SMF). At both splicing points, the HCPCF air holes are fully collapsed by the arc discharge. The collapsed regions excite and recombine core and cladding modes which formed modal interference for sensing purpose. The HCPCF sensor is tested in sugar solution and the response is measured from the wavelength shift in the interference spectra. The achieved sensitivity and resolution are 36.184 nm/RIU and 5.53×10^{-4} RIU, respectively, in refractive index range between 1.3330 and 1.3775. Result also shows that the sensor has a small temperature sensitivity of 19 pm/°C in the range of 35.5°C to 60.5 °C. The proposed sensor potentially can be applied in biomedical, biological and chemical applications.

Keywords: refractive index, sensor, hollow core, photonic crystal fiber, modal interference.

INTRODUCTION

In the last few years, market for fiber optic sensors has been rapidly growing and developing. This is undoubtedly due to the many desirable advantages of fiber optic sensor over conventional electrical sensor such as their compactness, robust and lightweight structure, absolute measurement capability, low loss, high resolution, immunity to electromagnetic interference, and suitability for in-situ and remote measurements. Fiber optic sensors play a critical role in meeting the needs of our evolving technology. Optical techniques developed for sensing purposes have been proven to be beneficial in many applications because of its capability to monitor physical quantities such as pressure [1], strain [2], temperature [3] and displacement. In recent years, the use of fiber optic sensors for detection of refractive index has gained more interest. Refractive index sensing is essential for medical, biological, and chemical applications as elements concentration can be determined through the measurements of refractive index change.

There are numbers of techniques that have been proposed for refractive index sensing, which are typically based on modal interference technique. This type of sensor can be easily constructed by successive splicing between different types of fiber in order to excite cladding modes which creates interference effect with the core mode. Photonic crystal fiber (PCF) is one of the suitable fibers that can be implemented as the sensing head due to its good sensitivity for refractive index measurement whilst less sensitive to temperature disturbance. Furthermore, the holey structure of HCPCF possesses unique modal properties and light guiding mechanisms that are impossible with conventional optical fibers. Recently, new interferometers with collapsed splicing have been demonstrated [4-8]. This approach is considered much simpler and convenient as it only involves the process of cleaving and splicing, which can be easily conducted in optical laboratory.

One of the developed PCF techniques for refractive index measurement is based on hybrid Fabry-Perot (FP) and modal interferometer [4]. An air bubble is purposely formed in the splice region to form FP cavity. The maximum sensitivity achieved is 21.4 nm/RIU for refractive index between 1.33 and 1.4. A direct splicing of solid core photonic crystal fiber (SCPCF) with single mode fiber (SMF) at both ends allowing a collapsed region to be created at the splicing region for coupling and recombination of PCF core and cladding modes [5]. The maximum sensitivity attained in this scheme is ~40 nm/RIU with resolution of 2×10^{-3} RIU. In other work, a SCPCF based fiber tip refractive index sensor in reflection manner is demonstrated [6] with achieved maximum sensitivity of ~100 nm/RIU and resolution of 10^{-4} RIU. A SCPCF refractive index sensor spliced to SMF at both ends in SMF-PCF-SMF configuration is demonstrated [7]. The maximum sensitivity achieved with ~3 mm PCF section is 70.2 nm/RIU for refractive index range of 1.33~1.35. In other work, a SCPCF coated with SiN_x nano film in similar SMF-PCF-SMF configuration attained a maximum sensitivity of 874 nm/RIU [8]. A refractive index sensor based on two large-core air-clad PCF is demonstrated with maximum sensitivity and resolution of 800 nm/RIU and 3.4×10^{-3}, respectively [9]. A hollow core photonic crystal fiber (HCPCF) which is butt-coupled to SMF has achieved very high sensitivity of -5000 nm/RIU attributed to direct interaction of light with measurand [10]. Over recent years, it has been shown that the PCF-based refractive index sensors can easily achieve ultrahigh sensitivity, up to 1000 times relative to the prism-based conventional refractive index sensor. Modifications such as applying metal coating or filling the air holes with tested liquid will greatly enhance the sensitivity of the refractive index sensor. Nonetheless, sensor construction becomes more complex and expensive. Filling the PCF air holes with liquid renders the refractive index sensor a one-time-usable sensor. The filling process is time consuming due to the micro-sized hole of PCF.

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In this paper, we propose and demonstrate a refractive index sensor based on HCPCF. The refractive index sensor is constructed by splicing both ends of a HCPCF section to single mode optical fibers (SMF). At both splicing points the HCPCF air holes are fully collapsed by the arc discharge during splicing. Light guided from the single mode fiber (SMF) diffracts when it reaches the collapsed region of the PCF. The diffraction leads to mode broadening and the excitation of core and cladding modes in PCF section. As a result, the higher order modes can be excited efficiently to form modal interference for sensing purpose.

THEORY AND SENSING PRINCIPLE

In the PCF-based modal interferometer, light guided from the single mode fiber (SMF) diffracts when it reaches the collapsed region of the PCF. The diffraction leads to mode excitation into core and cladding in PCF section. The propagation constants difference between core and cladding modes resulting to a phase difference. Figure-1 shows the schematic and sensing mechanism of the HCPCF sensor.

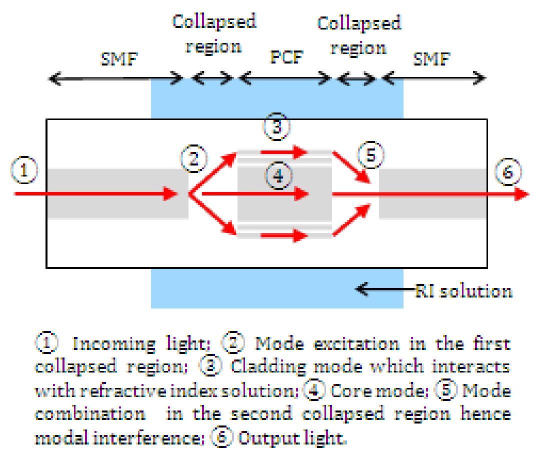

Figure-1. Schematic and light transmission of the HCPCF sensor.

The phase difference depends on the wavelength of the guided light and also on the travel distance of the modes. Further diffraction occurs and the light will be recombined when the modes reach another collapsed end. This results in the forming of modal interference for sensing purpose. Thus, the transmission of this interferometer can be written as:

$$T = I_{co}(\lambda) + I_{cl}(\lambda) + 2[I_{co}(\lambda)I_{cl}(\lambda)]^{1/2}\cos(\frac{2\pi\Delta nL}{\lambda}) \quad (1)$$

where I_{co} and I_{cl} are the intensities of the core and cladding modes; Δn is the difference between the refractive indices of core and cladding modes; L is the length of HCPCF section; and λ is the operating wavelength. Equation (1) shows that the interferometer transmittance exhibits a series of periodic maxima and minima. The maxima of transmission will appear at wavelengths [5]:

$$\lambda_m = \frac{\Delta nL}{m} \quad (2)$$

where m is an integer. Therefore, refractive index difference between these two modes is related to the fringe periodicity, S of the modal interference, which can be written as [11]:

$$S = \lambda^2 /(\Delta nL) \quad (3)$$

Equations (1) to (3) show that the modal interferometer is sensitive to the variations of Δn and L.

EXPERIMENT

Sensor splicing

The model of HCPCF used is HC-1550, a 7-cell hollow core fiber manufactured by NKT Photonics. It is designed to have a central wavelength of 1550 nm, core diameter of 10 µm and cladding diameter of 120 µm. The splicing machine (Fujikura FSM 17S) is set to manual mode to allow the user to change the setting prior to the arc fusion. The default SMF-SMF splice setting is set using the following settings:

Arc Power:	25 - 40 bit
Arc time:	3000 - 3700 ms
Gap:	33 - 30 µm
Arc offset:	5 µm (towards the SMF-side)

The above setting allows the SMF-HCPCF splice to be performed successfully. Adjustment of arc power and arc is necessary to avoid damage to the HCPCF and ensure that the air holes are fully collapsed. The arc position is offset longitudinally towards the SMF side to gives more heat to SMF than HCPCF. Prior the arc, the axial offset is set to zero. However, due to the movement of the V-groove of the splicer and the difference between cladding diameters, the core offset become ~1 µm after the arc. The proof test will pull the HCPCF and SMF apart and thus is disabled.

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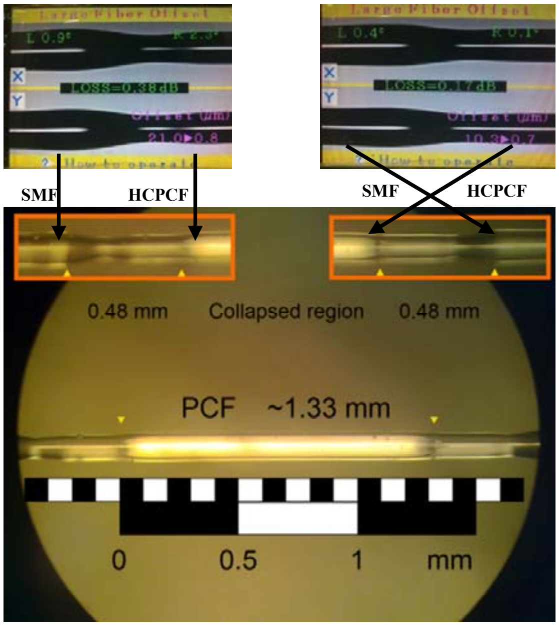

Figure-2. Top: Splice result of the left end and right end of the HCPCF. Bottom: Image of HCPCF under microscope.

Figure-2 shows the images captured from splicing machine and from microscope (Nikon Eclipse L150). The HCPCF length is ~1.33 mm. SMF has cladding diameter 5 μm larger than HCPCF cladding diameter, thus a taper is formed at the splice point. During the arc discharge, the air holes of HCPCF are collapsed. This further increases the difference in cladding diameter between SMF and HCPCF. In the bottom image, the length of uncollapsed HCPCF and the length of collapsed region are shown. The lengths are calculated by pixel counting.

Experiment setup

Experiment setup to measure HCPCF refractive index sensor response is shown in Figure-3(a). A C-band amplified spontaneous emission (Photonic P-ASE-C-20-NF-F/A) source with a full width at half maximum of 60 nm and output power of 11.8 mW is used to illuminate the sensor. The HCPCF is spliced in both ends to SMF of FC connectors. An optical spectrum analyzer (ANDO AQ6317B) is used to monitor the spectrum changes as the refractive index value is increased by increasing sugar concentration in water solution. The HCPCF sensor is suspended in a certain way as shown in Figure-3(b) so that addition or removal of sucrose solution will not cause any disturbance to the sensor that could cause error to measurement.

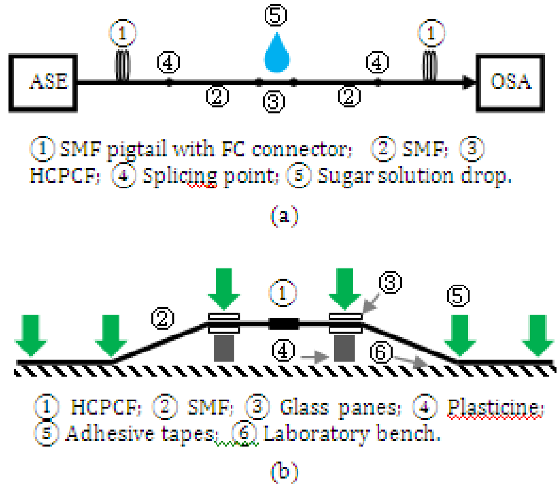

Figure-3. (a) The experimental setup for measuring response of the sensor at different refractive index, (b) arrangement of RI sensor suspension for testing.

Refractive index calibration

By using a calibrated brix refractometer (ATC) and brix chart, different concentrations of the sugar solution are prepared for the experiment. By varying the sugar concentration, refractive indices from 1.3330 to 1.3775 are obtained. Before each measurement, the sensing part is flushed with distilled water and blown to be dry. Table-1 shows the refractive indices of sugar solution with different concentrations. A digital thermometer (Fluke 54 II B) is used to monitor the ambient temperature. A temperature variation of ~2ºC has been recorded throughout the measurement. This temperature is near to the required temperature and minimum correction is required. The Brix meter operating temperature is between 10 and 30ºC with automatic temperature compensation. The temperature sensitivity of the refractive index sensor based on HCPCF is also being tested by continuous heating of the sensor underwater from 35.5°C up to 60.5°C.

Table-1. Refractive indices of sucrose solution with different concentrations.

Concentrations (%)	Refractive indices
0	1.333
6	1.3417
13	1.3525
22	1.3672
28	1.3775

RESULT AN DISCUSSIONS

Liquid samples with refractive indices of 1.333, 1.3417, 1.3525, 1.3672 and 1.3775 are used for the refractive index measurement. Figure-4 shows the transmission spectra of the HCPCF sensor at different refractive indices varied from 1.3330 to 1.3775. The

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sucrose solution is added to the sensing head to examine the influence of the refractive index on the transmitted light. The wavelength separation between the adjacent dips is about 15 nm.

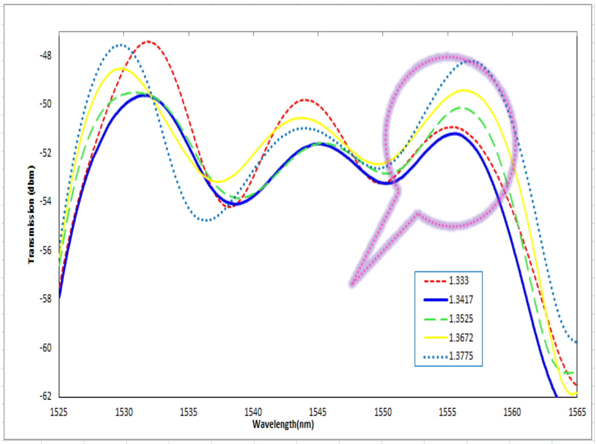

Figure-4. Transmission spectra of the refractive index sensor based on HCPCF with different refractive indices.

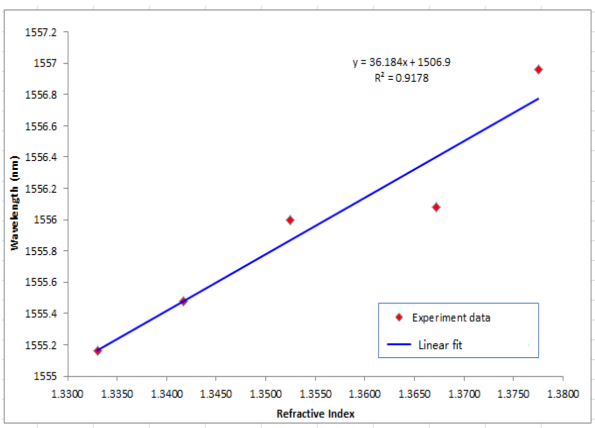

Figure-5. Peak wavelength shift of the HCPCF based interferometer versus refractive index.

Apparently, there are three peaks and two dips in the transmission spectra, each one with different response. Upon inspection of all peaks and dips, it is found out that the third peaks (circled) exhibits near to linear response. The dip wavelength shifted from 1555.16 nm to 1556.96 nm, corresponding to a total wavelength shift of 1.8 nm, as shown in Figure-5. Thus, the attained sensitivity is 36.184 nm/RIU. The resolutions of refractive index measurement for this range is ~5.53×10^{-4} RIU, considering a wavelength resolution of 0.02 nm of the OSA used in the experiment, which is comparable to other refractometers [5, 6].

Figure-6 shows the wavelength shift of the dips with the increase of water temperature. Power spectra of HCPCF is shifted due to the difference between thermo-optical of silica and air. When the temperature is increased from 35.5 to 60.5°C, the wavelength of the dip in the transmission is changed from 1531.6 to 1532.2 nm, which is a total wavelength shift of 0.6 nm. The wavelength shift of the dip has almost a linear relationship with the temperature change with temperature sensitivity of ~19 pm/°C, which is shown in Figure-7. The temperature variation could affect the resolution of the refractive index. In practical case to measure refractive index, it is necessary to add temperature compensation mechanism to avoid unwanted disturbance caused by temperature. Nonetheless, the temperature dependence is quite small compared to the typical response of modal interferometer.

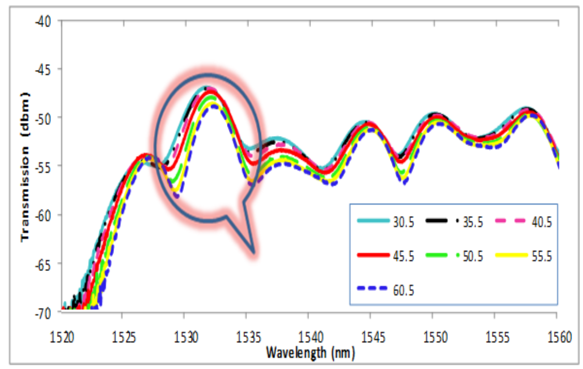

Figure-6. Transmission spectra of the refractive index sensor based on HCPCF with different temperatures.

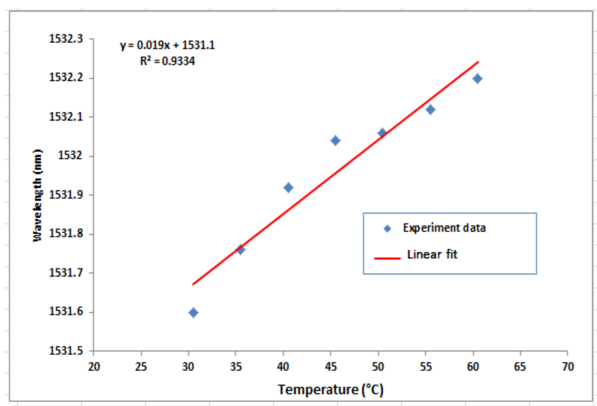

Figure-7. Peak wavelength shift versus temperature.

CONCLUSIONS

In this paper, a refractive index sensor based on modal interferometer HCPCF is proposed for refractive index sensing. The sensor can be simply constructed by splicing both ends of a HCPCF section to SMF. Thus, collapsed regions are created at these splicing points where core and cladding modes are diffracted and recombined to form modal interferometer for sensing purpose. The sensor has the sensitivity of 36.184 nm/RIU, with resolutions of 5.53×10^{-4} RIU for refractive index range between 1.3330 and 1.3775. This performance is comparable to the other type of optical refractive index sensor. The sensor also exhibits small temperature sensitivity of 19 pm/°C in temperature range between 35.5°C and 65.5°C. The sensor can be easily constructed by conventional splicing process. Moreover, the proposed

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sensor has the advantages such as reuse, small and flexible size, simple and convenient fabrication, and an all-fiber structure. Therefore, it will open new prospects in the biomedical, biological and chemical sensing fields.

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