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Multi-point fiber-optic refractive index sensor by using coreless fibers

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ABSTRACT

We present a novel multi-point fiber-optic refractive index (RI) sensor based on two different length coreless fibers spliced between single mode fibers (SMFs). The sensing probe operated based on multimode interference. A multi-point interferometer with 25 mm and 30 mm coreless fiber is fabricated and the measurement of RI is realized by measuring the wavelength shift of resonance dips in the transmission spectrum of the multi-point interferometer. Experimental characterization for a multi-point refractometer is presented. In the RI range of 1.3288–1.3666, the corresponding RI sensitivities are 148.60 nm/RIU and 119.27 nm/RIU for each point, respectively. We demonstrate that this multi-point fiber optic interferometer can be used as a simple transducer for RI sensing with comparable sensitivity.

1. Introduction

Multimode interference (MMI) has been thoroughly investigated as an attractive technology for optical communication and sensing [1]. Meanwhile, an increasing number of all-fiber multimode interferometer have been used for sensing applications, including temperature, strain, pressure, refractive index, and curvature sensing [2–14]. Typically, an all-fiber MMI is consist by a step-index multimode fiber (MMF) spliced between two single-mode fibers (SMF), forming a single mode–multimode–single mode (SMS) structure [3,8]. When the core mode of the lead-in SMF enters the MMF section, several high-order modes are excited and propagated along the fiber, at the other splicing point, the high-order modes are coupled back to the core mode of the lead-out SMF where interference occurs among the cladding modes. Recently, a fiber tip sensor for liquid level measurement is reported [14]. The sensing structure is constitute by a 125 μm diameter coreless-MMF section spliced to an SMF, and the MMF tip is coated with a 200 nm gold layer acting as mirror, so that the self-image is reflected and coupled back into the SMF. Therefore, when the length of coreless MMF immersed in a liquid changed, a correlated shift of the wavelength peak is observed. Moreover, another SMS fiber-based refractometer based on the self-imaging is proposed [7]. A core-etched MMF with different diameters is used to attempt to investigate diameter influence on the sensitivity to RI measurement. In the RI range from 1.345 to 1.43, experimentally, SMS fiber-based refractometers with 50, 80, and 105 μm core diameters are analyzed; numerical results have shown that the sensitivity to external RI increased with the MMF core diameter decreasing. Meanwhile, fiber optic structures based on multimode interference are also investigated to RI sensing [15,16]. The proposed device is a SMS structure, where the multimode fiber is a coreless fiber, and the numerical analyses are carried out by beam propagation and modal expansion methods. Finally, they present and demonstrate a SMS multimode interference structure based on standard single mode fiber and multimode coreless fiber verified the built with.

In this paper, we present and demonstrate a novel multi-point fiber-optic RI sensor based on multimode interference. Each point consists of a section of coreless fiber with a selected length. Experimental results show that the sensor has high RI sensitivity and the wavelength shift of the resonance peaks as a linear function of RI. The resonance wavelengths of the points shifted towards the longer wavelength while the RI increases. Compared with other aforementioned fiber refractometers, the fabrication of this multi-point fiber optic interferometer is simple and cost-effective, this multi-point sensor also can applicable to on-line detection in any environment containing multiple targets as well as for some measurement processes that required self-inspection.

2. Experiments and discusses

Fig. 1 illustrates the multi-point fiber optical sensor system by using coreless-fiber. Fig. 1(a) is a cross-section profile of the coreless fiber and SMF, the coreless fiber is made up of silica with a refractive index as 1.440, a lay of polyimide coating is used as its' buffer. The schematic of experimental setup is shown in Fig. 1(b), a broadband source (BBS) in the 1550 nm spectral range with a bandwidth of 200 nm and an OSA (AQ6370, Yokogawa) are used to

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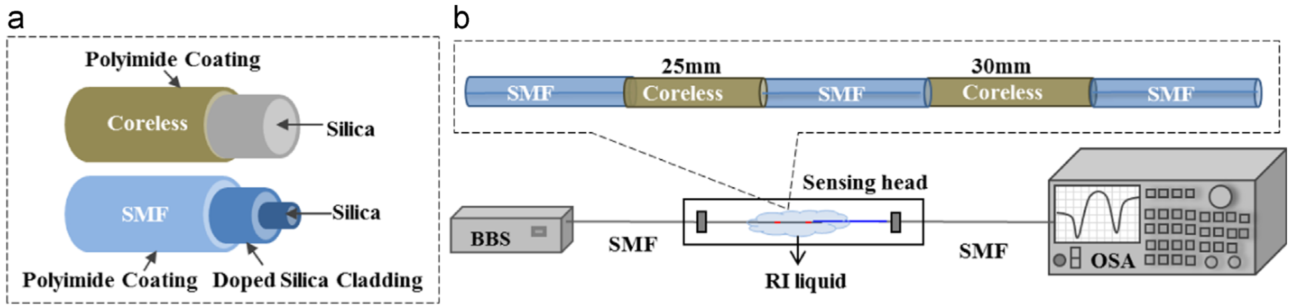

Fig. 1. Schematics of coreless-fiber based multi-point sensor system. (a) Cross-section profile of the coreless fiber and SMF; (b) sensing system experimental setup; insert is the dual-channel refractometer structure built with different lengths coreless fiber of 25 mm and 30 mm.

measure the spectrum. The light from the light source transmits through single mode fiber into the sensing area where a multi-mode interference occurs, and then along the single mode optical fiber, the light signal is transmitted to the spectrometer for signal collection and analysis. The sensing area includes two coreless optical fibers with different lengths as 25 mm and 30 mm separately, which is shown in Fig. 1(b).

Firstly, we fabricate and test 20 mm, 25 mm, and 30 mm length sensors for RI measurement at room temperature (25 °C) using the experimental setup as shown in Fig. 1(b). During the test, all fibers are aligned along the same axis and possessed a circular cross section and the sensor is kept straight with the help of two fiber holders. Sodium chloride solutions of different concentrations in deionized water are used as samples with different RIs. The solution's RI is measured by an Abbe refractometer with a 1.3288–1.3666 RI range. Before each measurement, we clean the sensor by deionized water and dried in air. In our experiment the sensor is totally immersed into the sample which is injected by a pipette.

The transmission spectra of sensors with different coreless fiber lengths of 20 mm, 25 mm and 30 mm is shown in Fig. 2. It can be seen that the transmission spectra are different for different coreless fiber length and each curve at least has two obvious notches. Moreover, as the coreless fiber length increasing, the wavelengths of the dips will drift. The experimental results show that lengths of coreless fiber have effect on multimode interference just as the coreless fiber with different radius make multimode interference changed [15,16].

For RI measurement, the sensors with different coreless fiber lengths are further tested, respectively. Fig. 3 shows the transmission spectra of three sensors with two notches response to RI. Two spectral dips shift to longer wavelength as the RI of the external sample increase. The external RI affects the effective RI of different modes in the coreless fiber differently. From the data, we know there are more than two digs in sensors of different lengths, and each dig can be used as measuring point. In the measuring process, the data of these two digs can be collected to prove the validity of the results, one of them can be used as a stability calibration point for the other dip, which monitoring their respective changes, and reflecting the testing correctness. The spectral shifts as a function of external RI for both spectral notches as well as their linear fitting are shown in Fig. 3(a), (b) and (c). The corresponding RI sensitivities are 113.41 nm/RIU, 140.88 nm/RIU and 125.15 nm/RIU for three sensors, respectively.

Based on the analysis of different lengths coreless optical fiber refractometer graph, the sensors of different length sensing area have different reaction locations, and the dip position will move to the long wavelength with the length of the sensing area increase. To use the light path effectively, this dual-point sensor is not made of two single point sensors directly. Three single mode optical fibers and two coreless optical fibers with the length of 25 mm and 30 mm are selected to joint for one sensor, get a dual-point

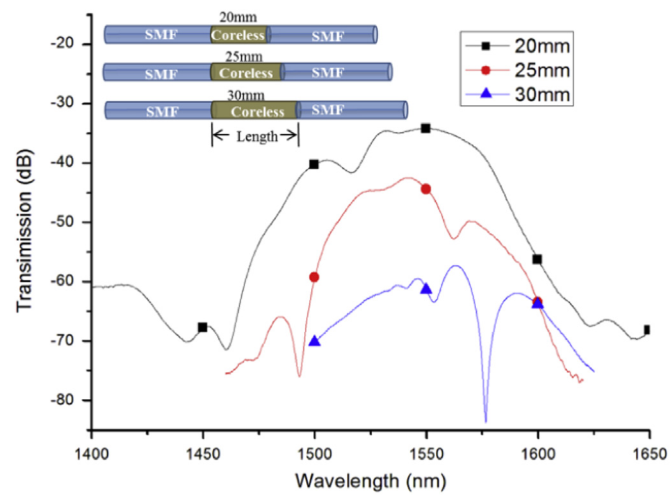

Fig. 2. The transmission spectra of sensors with different coreless fiber lengths; the inset multimode interference structure are built with standard single mode fibers and coreless fibers.

refractometer. In the same way, we put it at the experimental setup as shown in Fig. 1(b) and have RI measurement. Figs. 4 and 5 illustrate the RI test results of the sensor which has two dips corresponding two points in the transmission spectrum. Fig. 4 shows the wavelength and spectral responses of point 1 with the coreless fiber length of 25 mm to different RI values, while the wavelength and spectral responses of another point 2 with the coreless fiber length of 30 mm is shown in Fig. 5.

Figs. 4(a) and 5(a) show that the dual-point sensor has two obvious dips. In the experiment of Fig. 4, we make the point 2 in aqueous solution all the time, but make the point 1 under test of refractive index changing from 1.3288 to 1.3593. Fig. 4(a) is the transmission spectra with two dips response to RI. Fig. 4(b) shows that the spectral dips of point 1 shift to longer wavelength as the RI of the external sample increase, but the point 2 has no change within the error rang allowed. In the same way, in the experiment of Fig. 5, we make the point 1 in aqueous solution all the time, but make the point 2 under test of refractive index changes from 1.3288 to 1.3593. Fig. 5(a) shows the transmission spectra with two notches response to RI. Fig. 5(b) shows the spectral dips of point 2 shift to longer wavelength as the RI of the external sample increase, but the point 1 also has no change within the error rang allowed. We get the corresponding RI sensitivities are 148.60 nm/RIU and 119.27 nm/RIU for each point, respectively. Experimental results show that both points do not have influence on each other in the process of measuring, and the refractometer can be used as a dual-point sensor.

We used two single point sensors to construct a dual-point sensor, and we measured them respectively and get the following spectrum. From the spectrum, we know dip 1 is from the sensor

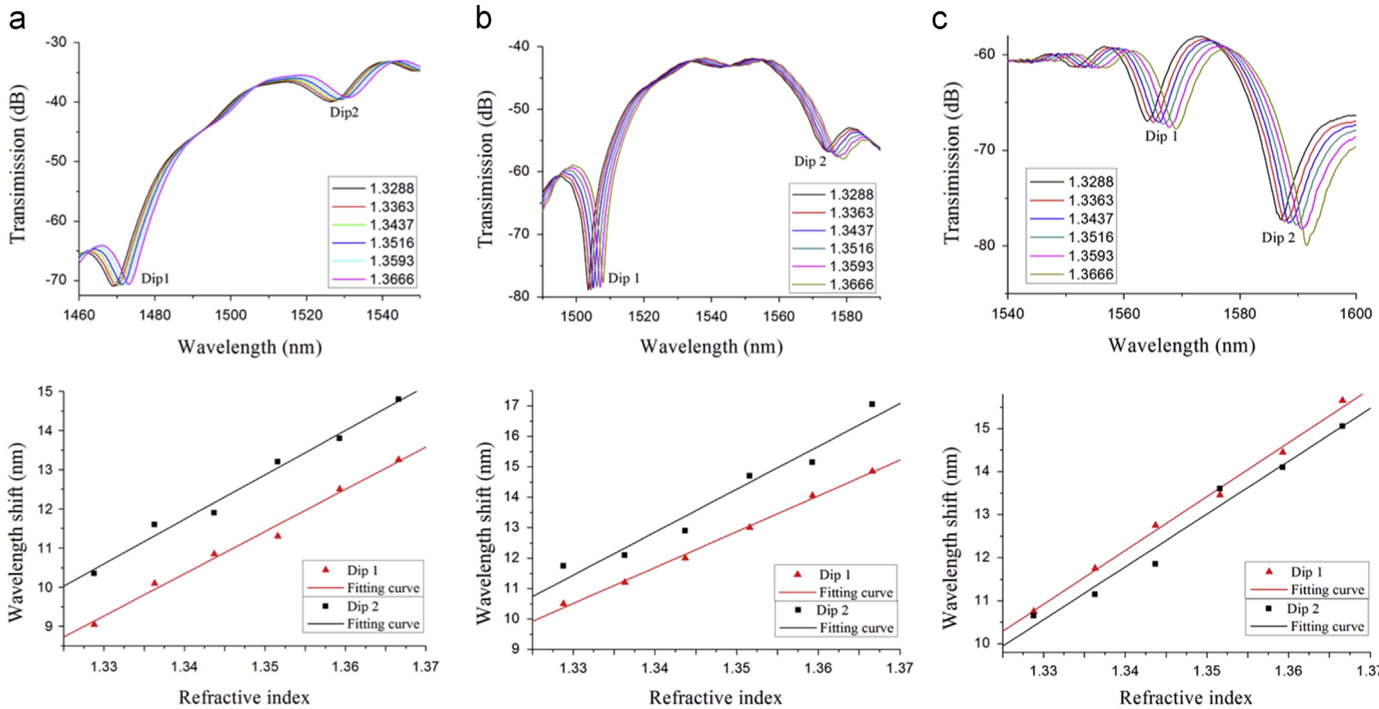

Fig. 3. Transmission spectra with two notches response to RI based on the proposed sensors with different coreless fiber length (a) 20 mm; (b) 25 mm; (c) 30 mm.

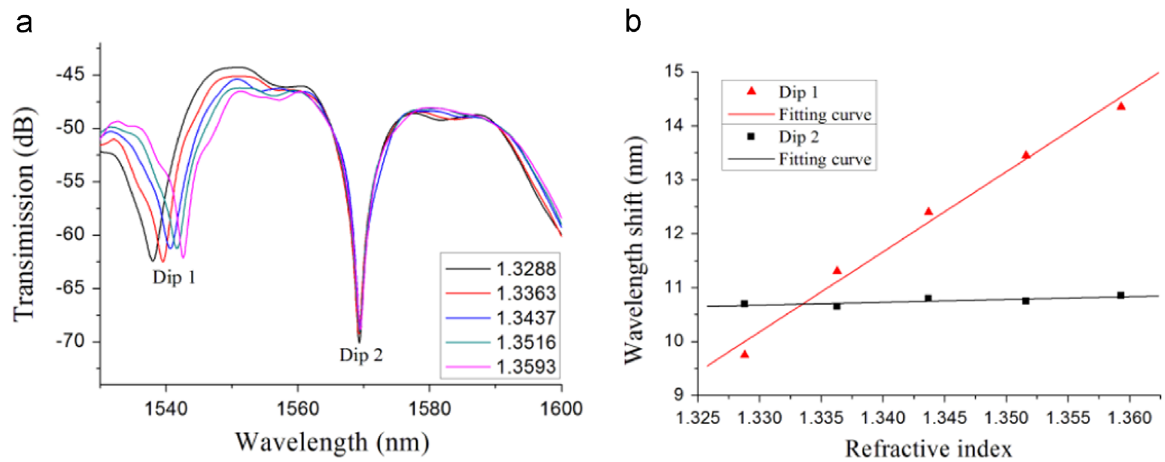

Fig. 4. Spectral characteristics of point 1 in RI measurement. (a) Depicts transmission spectra with two notches response to RI; (b) RI response of dual-point structure sensors.

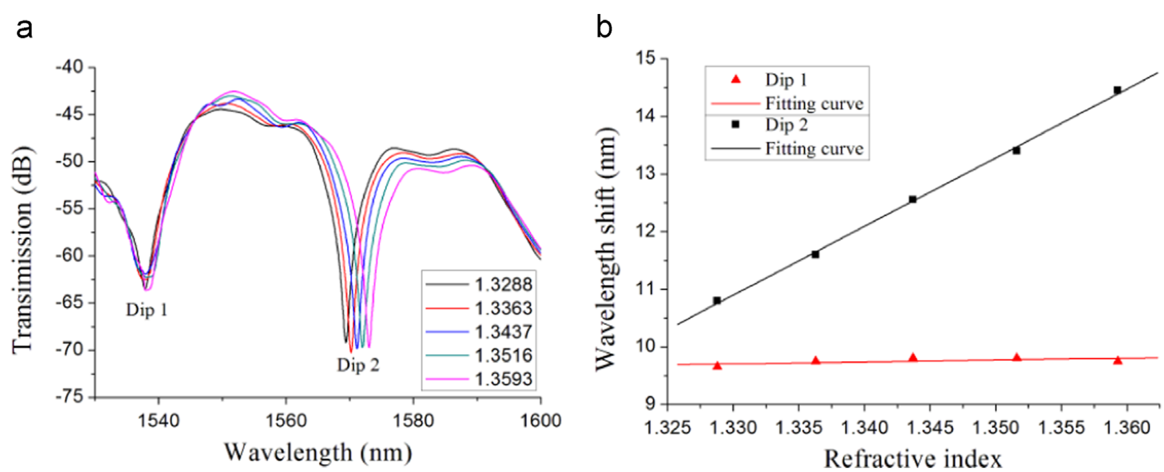

Fig. 5. Spectral characteristics of point 2 in RI measurement. (a) Depicts transmission spectra with two notches response to RI; (b) RI response of dual-point structure sensors.

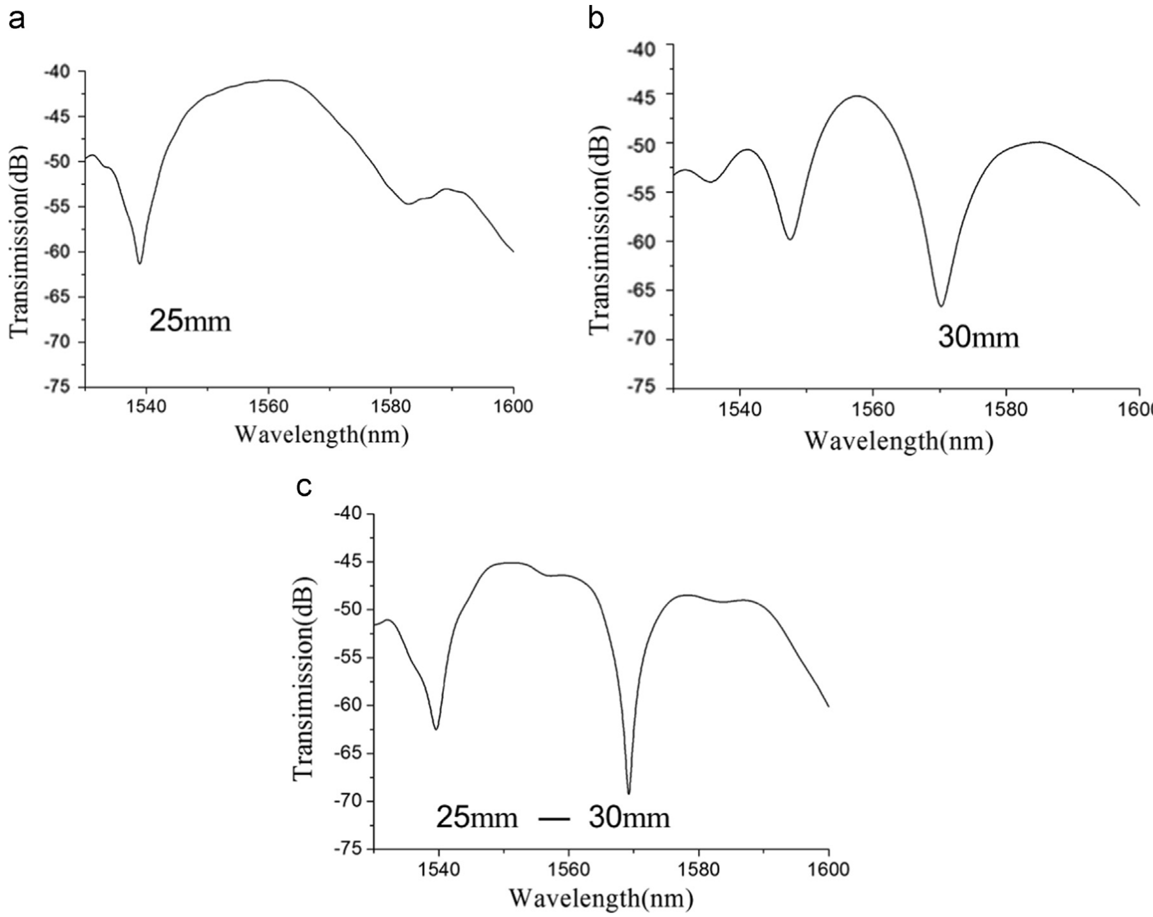

Fig. 6. Transmission spectra with different coreless fiber length (a) 20 mm; (b) 25 mm; (c) 25 mm–30mm.

with coreless fiber length of 25 mm, and dip 2 belongs to the sensor with coreless fiber length of 30 mm. Connecting these two sensors together, we get the dual-point sensor as we presented in this work (Fig. 6).

3. Conclusions

In conclusion, we proposed and demonstrated a novel multi-point fiber optic refractometer based on modal interference in the coreless fiber between SMFs for high sensitive RI sensing. Experimental data showed this sensor has a quadrature response with a high sensitivity for the tested RI range from 1.3288 to 1.3666. Based on the investigation of the sensors with different coreless fiber lengths, we made this multi-point refractometer, in which each sensing point responses to different refractive index solution, also they are independent of each other during the measurement. This sensor has some advantages including miniaturization, low cost, simple fabrication process, and robustness. The coreless fiber could be conveniently coated with functional materials to achieve higher sensitivity and better selectivity for some biological or chemical parameters other than RI. This optical coreless fiber based sensor has potentially attractive for bio-chemical and biomedical applications.

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