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Multi-parameter optical fiber sensor based on enhanced multimode interference

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ABSTRACT

In this paper, a multi-parameter optical fiber sensor based on all-fiber in-line single-mode-multimode-no-core-single-mode (SMNS) structure is proposed and experimentally demonstrated. A section of multimode fiber (MMF) is utilized as the mode coupler to enhance the multimode interference (MMI). A 58.5 mm long no-core fiber (NCF) acts as the sensing head, which is modified by the surrounding medium. The experimental results exhibit that the sensor possesses a water level sensitivity of 215.98 pm/mm by monitoring the wavelength shift at 1586.03 nm, and −0.11 dB/mm of the power attenuation at the wavelength of 1600.05 nm with a measurement range of 58.33 mm. At the same time, the RI sensitivities of 131.71 nm/RIU and the axial strain sensitivity of −1.21 pm/με are also obtained.
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1. Introduction

Optical fiber sensors have been extensively researched for the applications in food security, chemical and biological industries, civil infrastructures and environmental monitoring with the innovation of the optical fiber technology. Nowadays, optical fiber sensors become promising candidates for various measurands due to many distinguished advantages, such as low cost, high sensitivity, compact size, immunity to electromagnetic interference, resistance to erosion and the application of distributed remote sensing [1,2]. To author's best knowledge, several kinds of optical fiber sensors such as long period fiber gratings (LPFGs) [3–7] fiber Bragg gratings (FBGs) [8–11], tapered fibers [12–16] and in-fiber micro-cavities [17] have been proposed and demonstrated in the sensing applications of RI, liquid level, temperature and vibration. Though these sensors show excellent performance, the high cost of fabrication and fragility of the sensor head restrict their extensive applications. Recently, fiber in-line structure sensors based on Mach–Zehnder interference (MZI) have attracted considerable attentions [18–20]. Li et al. proposed a single-mode-multimode-thinned-single-mode (SMTS) fiber structure for liquid level, RI, temperature and axial strain measurements [19], but the sensitivities have yet to be improved. Shao et al. presented a single-mode-thin-core-multimode-single-mode (STMS) fiber structure for RI measurement with a high sensitivity [20], while the fabrication of the multimode fiber core is complicated and unsafe. Meanwhile, for the two sensors mentioned above, the splicing of the fiber with different diameters also partly limits their applications.

Optical MMI devices based on self-image was illustrated in 1995 [21]. And since 2003, several works with SMS fiber structure based on MMI in fiber optic sensing applications have been reported owing to the unique advantages of easy fabrication, compactness and practicability [22]. The general operation principle of various SMS structure derives from the influence of external perturbation on MMI. In this paper, a new multi-parameter optical fiber sensor based on all-fiber in-line SMNS structure for liquid level, RI and axial strain sensing applications is proposed and experimentally demonstrated. The principle of MMI and multi-parameter measurements are elucidated in detail. The wavelength-shift demodulation scheme is used to monitor the variation of multiple parameters, and the optical power attenuation at specific wavelength is also applied to the measurement of liquid level. Based on the experiment, the proposed structure shows high sensitivities to liquid level, RI and axial strain with fairly good linear responses.

2. Schematic diagram and operation principle

The schematic diagram of the sensor is shown in Fig. 1. A segment of NCF is spliced to MMF, and then this section is sandwiched in a segment of SMF. The NCF has a diameter of 125 μm with the RI of 1.457. The core/cladding diameters of SMF and MMF

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Fig. 1. Schematic diagram of the SMNS fiber structure.

are 9.2/125 μm and 50/125 μm, respectively. All the fibers utilized in the experiment are produced by the Yangtze Optical Fiber and Cable Company Ltd. The MMF acting as a mode coupler is conducive to the formation of a stable and large mode field pattern in the MMF compared to SMF. The key component of the sensor is a segment of NCF with a length of 58.5 mm. It is selected to get a prominent self-image [23]. When the light is launched into the MMF through the lead-in SMF, a series of linearly polarized modes (LP_{lm}) are excited from the fundamental mode (LP_{01}) at the SMF–MMF interface owing to the mode field mismatch. And then a large mode field pattern propagates in the MMF compared to SMF. It is noted that in consideration of the circular symmetry of the fiber structure, the multiple modes excited from the fundamental mode of the SMF are symmetric modes (LP_{0m}) [24]. Similarly, at the MMF–NCF interface, multiple modes are excited again from the Eigen modes of the MMF because of the mode field mismatch. Owing to the differences between the longitudinal propagation constant (β) of the multiple modes, the interference between the LP_{0m} happens along the NCF and results in the formation of self-image at the NCF–SMF interface. In this process, the MMF acts as a mode coupler, which provides twice multimode excitation from the lead-in SMF to NCF. Compared to traditional single-mode-multimode-single-mode (SMS) structure, more power of the fundamental mode can be decomposed into the multiple symmetric modes.

According to [23], the peak wavelength of the self-image induced by the MMI can be expressed as

$$\lambda = \frac{qN_{NCF}D_{NCF}^2}{L} \quad \text{with } q = 1, 2, 3\ldots, n \tag{1}$$

where N_{NCF} is the effective refractive index, D_{NCF} is the diameter of the fundamental mode of the NCF, and λ is the peak wavelength of the self-image. L is the geometry length of the NCF and q is the number of the self-image. In order to obtain a self-image with minimum insertion loss and narrow spectral bandwidth at the measurement spectral range, the sensor is managed to operate at the fourth self-image ($q=4$) by controlling the length of the NCF.

As shown in Fig. 2, when a section of the NCF is surrounded by liquid, the effective refractive index and diameter of the fundamental mode increase compared to the section in the air, which leads to a redshift of the peak wavelength. It can be seen that the NCF is broken up into two sections with different cladding (surrounding medium) RIs. Hence, the peak wavelength of the fourth self-image can be modified as [23]

$$\lambda = \frac{4N_{NCFn}D_{NCFn}^2L_{liq}}{L^2} + \frac{4N_{NCF0}D_{NCF0}^2L_{air}}{L^2} \tag{2}$$

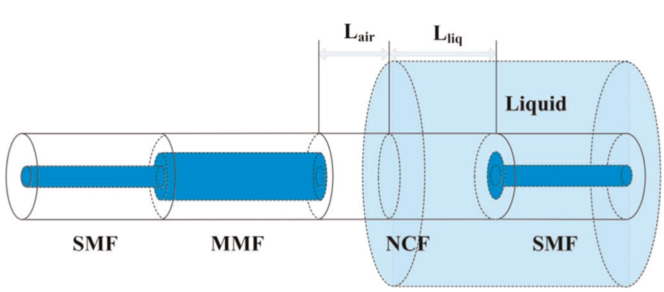

Fig. 2. Schematic diagram of liquid level sensing.

where the first part corresponds to the in-liquid section and the second is in-air. L is the overall length. L_{liq} and L_{air} are the in-liquid length and in-air length of the NCF, respectively. N_{NCFn} and D_{NCFn} are effective refractive index and diameter of the fundamental mode for in-liquid section. N_{NCF0} and D_{NCF0} represent the in-air ones. Experimentally, we can measure the variation of liquid level via monitoring a redshift of the peak wavelength. Assuming that RI of the liquid is constant, the liquid level measurement sensitivity referring to wavelength shift can be estimated from

$$\frac{\partial\lambda}{\partial L_{liq}} \approx \frac{4D_{NCF0}(2N_{NCF0}\Delta D_{NCF} + \Delta N_{NCF}D_{NCF0})}{L^2} \tag{3}$$

$$\Delta N_{NCF} = N_{NCFn} - N_{NCF0} \tag{4}$$

$$\Delta D_{NCF} = D_{NCFn} - D_{NCF0} \tag{5}$$

Here N_{NCF0} and D_{NCF0} are the effective refractive index and diameter of the in-air NCF fundamental mode. ΔN_{NCF} and ΔD_{NCF} represent the difference of the effective refractive index and fundamental mode diameter between the in-liquid and in-air sections, which are defined in Eqs. (4) and (5). In the condition of constant surrounding liquid RI, Eq. (3) illustrates that the sensor has a basically linear response to the variation of the liquid level and the sensitivity is determined by RI of the liquid.

In addition to the measurement method of wavelength shift, the variation of the liquid level can also be monitored by observing the optical power attenuation at a specific wavelength of 1600.05 nm. The reason is the holistic wavelength shift and the limitation of the spectrum of the optical light source. Moreover, when the NCF is surrounded by liquid, lower RI difference will shift the transverse field profile to the cladding (surrounding liquid), which also contributes to the attenuation. As a result, the optical power at the specific wavelength attenuates along with ascending liquid level.

Meanwhile, this fiber sensor shows an excellent performance on the measurement of refractive index. As expressed in Eq. (1), the increase of RI will shift the transverse field profile into the cladding (surrounding liquid). It leads to the variation of effective refractive index and diameter of the fundamental mode. Because of a small variation range of the RI, the effective refractive index can be supposed to remain invariant. In comparison, the increase of the fundamental mode diameter is dominant. Consequently, the wavelength redshift occurs.

Moreover, the fiber sensor is also a good candidate for the measurement of axial strain. When the axial strain is applied on the fiber structure sensor, the geometry length of NCF (L), effective refractive index and diameter of fundamental mode (N_{NCF} and D_{NCF}) will change. Considering that the variation of the fundamental mode effective refractive index is negligible, the decrease of the fundamental mode diameter and the elongation of the geometry length lead to a wavelength blueshift.

3. Experiments and discussions

In this section, the sensing applications in liquid level, RI and axial strain is experimentally demonstrated and further discussed. In our experiment, the fiber structure is fabricated by a fusion splicing technique. A combined C+L band optical light source launches the light into the structure, and an optical spectrum analyzer (AQ6370) with a resolution of 0.02 nm is utilized to monitor the variation of the transmission spectrum. A linear fitting is used to evaluate its response.

As shown in Fig. 3(a), the experiment of liquid level measurement is operated in such a setup. It consists of a beaker and a

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