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A fiber-optic sensor based on no-core fiber and Faraday rotator mirror structure

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ABSTRACT

An optical fiber sensor based on the single-mode/no-core/single-mode (SNS) core-offset technology along with a Faraday rotator mirror structure has been proposed and experimentally demonstrated. A transverse optical field distribution of self-imaging has been simulated and experimental parameters have been selected under theoretical guidance. Results of the experiments demonstrate that the temperature sensitivity of the sensor is 0.0551 nm/°C for temperatures between 25 and 80 °C, and the correlation coefficient is 0.99582. The concentration sensitivity of the device for sucrose and glucose solutions was found to be as high as 12.5416 and 6.02248 nm/(g/ml), respectively. Curves demonstrating a linear fit between wavelength shift and solution concentration for three different heavy metal solutions have also been derived on the basis of experimental results. The proposed fiber-optic sensor design provides valuable guidance for the measurement of concentration and temperature.

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1. Introduction

Optical fiber sensors based on the single-mode/multimode/single-mode (SMS) structure possess the advantages of simple structure, easy fabrication, low cost, good security, no electromagnetic interference, and so on [1–5]. In recent years, significant research has been conducted in this domain and many remarkable achievements have been recorded. Owing to their excellent performance, SMS fiber-optic sensors have found applications in transportation, food, biological, chemical, medical, and such other fields to perform measurements of numerous parameters [6–8]. Based on the multimode interference theory, SMS fiber-optic sensors are not only used as filters but are also widely employed in the measurement of temperature, concentration, curvature, stress, liquid level, etc. [9–13], thereby exhibiting broad prospects for development.

The importance of accurate measurement of temperature and concentration in biology and medicine is paramount. Common interferometric sensors in present use include the multimode, Mach–Zehnder, and Fabry–Perot interferometers [10–11]. However, these sensors possess a complex structure and are relatively expensive. At present, the solution concentration-sensing structure, made of conventional single-mode and multimode fibers, features a low sensitivity and has no significant influence on the transmission characteristics of the optical fiber [12]. However, altering the shape of the optical fiber or thickness of the cladding to improve its sensitivity has led to difficult problems during fabrication, and the repeatability of the experiment is not sufficiently high [13]. Some recent studies have put forward sensing structures that employ the no-core core-offset [14–15] and single-mode no-core core-offset [16] techniques. However, they suffer from large attenuations and the output spectra are affected by the polarization state. Moreover, there is no clear theoretical guidance for selecting the length of the no-core fiber. All such problems have hindered the development of fiber-optic based temperature and concentration sensors.

Based on these findings, this paper proposes the use of a section of no-core fiber (NCF), instead of the multimode optical fiber used in the SMS structure, and splicing it with a Faraday rotator mirror (FRM) [17] to resemble a core-offset. In our study of the proposed sensor design, we not only analyzed the influence of various parameters on the output of the interference spectrum, in theory, but also performed experiments to investigate the relationship between different solution interference spectra and changes in the external environment. The FRM structure is used to acquire an output without any effect on the polarization state thereby improving the accuracy and efficiency of the measurement.

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2. Sensor fabrication and measurement principle

2.1. Sensor structure

The sensing structure based on the no-core fiber is depicted in Fig. 1. A broadband light source (BBS) having a central wavelength of 1550 nm is used throughout the experiment. An AQ6370C spectrometer has a scanning range of 600–1700 nm with a resolution of 0.02 nm. A certain length of NCF is fused between two parts of a single-mode fiber (SMF), and the single-mode/no-core/single-mode (SNS) structure is then spliced using the FRM in a manner similar to a core-offset. The cladding diameter of the NCF is 125 μm. The core and cladding diameters of standard SMF are 9.2 and 125 μm, respectively. The offset point value is 3.75 μm. All fibers used in this experiment are produced by the Fire Company. A commercial fusion splicer (K1-280, Nanjing Jilong Optical Communication Co. Ltd.) is used for welding these different components together to construct the SNS core-offset structure with FRM. Critical parts of the sensor are a segment of NCF that is 4 cm in length and FRM having a length of 35 cm. The former is chosen to obtain an outstanding self-image, while the latter is selected to acquire an output without any effect on the polarization state so as to improve the sensor's sensitivity [18].

To analyze the dependence of interference on the offset parameter, the same core-offset fiber was fabricated into two sets—one with different values of length (L) and the other with varying offset (D) of interferometer. The transmission spectra obtained by using different offsets and lengths of the interferometer are shown in Fig. 2. It can be seen that the interference pattern is affected by the varying offset and length parameters. For the sensor used in this study, a value of 3.75 μm was chosen for the offset (D) with due consideration of the tradeoff that exists between the offset size and insertion loss. Similarly, a sensor length of 4 cm was chosen as the optimum length for temperature and concentration measurement through interference intensity.

The optical signal emitted by the broadband light source is transmitted from SMF1 to NCF. A series of higher-order modes (LPnm) can be excited in the NCF owing to a mismatch of the mode field. When the axes of NCF and SMF1 are along the same straight line, only the symmetric modes (LP0m) are effectively excited. Similarly, when the incident light signal propagates along the axial direction from NCF to SMF2, only the symmetric modes (LP0m) in the NCF can be transmitted to SMF2. The external material of NCF can be considered as cladding layer. When the refractive index of this external material is perceived to be lower than that of the NCF itself, the SNS part can be equivalently regarded as a multimode interferometer (MMI) that the LP0m mode creates in NCF.

According to the theory of the multimode interference effect, the length L of the NCF section can be expressed as [16]

$$L = \frac{3 * k * L_\pi}{4}, k = 0, 1, 2, 3, 4 \tag{1}$$

where k is the self-image number and L_π corresponds to the beat length given by

$$L_\pi = \frac{16 * n_{cladding}^{eff} * R_{cladding}^2}{3 * \lambda_k} \tag{2}$$

Here, $n_{cladding}^{eff}$ corresponds to the effective refractive index of SMF-28 and NCF corresponding to a free-space wavelength of λ_k. R_{cladding} is the cladding radius for both SMF-28 and NCF.

NCF is also used as a beam splitter. As such, the light beams from NCF are divided into two parts; one part remains in the core while the other is transmitted along the cladding. The two optical signals then arrive at the core-offset point, which acts as a beam combiner. Two modes are coupled in the core of SMF3. An optical path difference is caused by the variation of refractive index of the core and cladding modes implying that interference can be generated.

In general, the interference intensity I can be expressed as

$$I = I_{core} + I_{cladding} + 2\sqrt{I_{\text{core}} I_{\text{cladding}}} * \cos(\phi) \tag{3}$$

After being reflected by the FRM, the phase difference ϕ between the core and cladding modes can be written as

$$\phi = \frac{4 * \pi * \Delta n_{\text{eff}} * L_2}{\lambda} \tag{4}$$

where λ is the wavelength in vacuum, L_2 is the length of SMF3, and Δn_{eff} is the effective difference between the refractive index of the core and cladding materials.

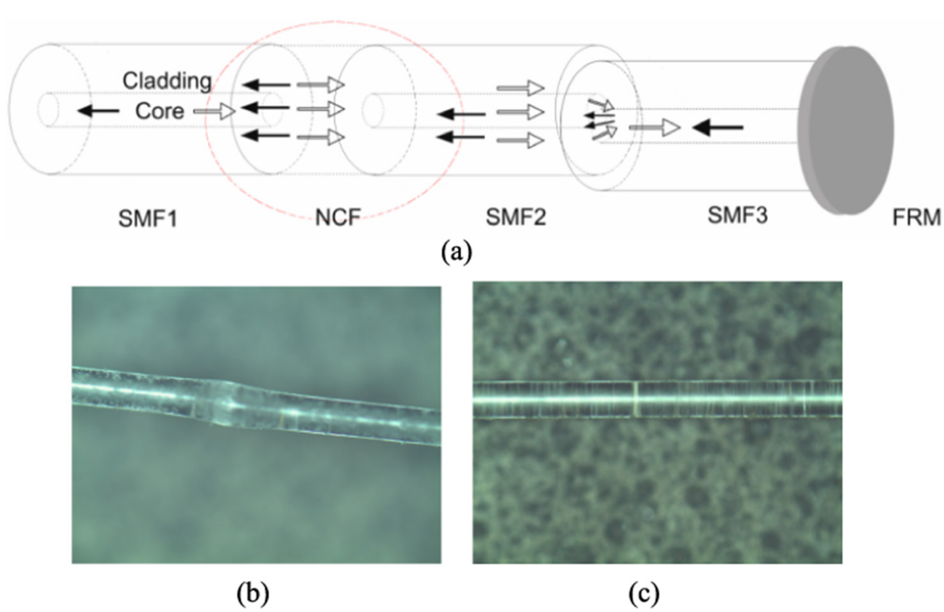

Fig. 1. (a) The 3D structure schematic of the sensing head made by fusing the SNS structure and Faraday rotator mirror; (b) Photograph of the core-offset section; and (c) Photograph of the NCF section under an optical microscope.

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