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Dual-point reflective refractometer based on parallel no-core fiber/FBG structure

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ABSTRACT

A novel dual-point reflective fiber-optic refractometer based on multimode interference (MMI) effect and fiber Bragg grating (FBG) reflection is proposed and experimentally demonstrated, which adopts parallel structure. Each point of the refractometer consists of a single mode-no core-single mode fiber (SNS) structure cascaded with a FBG. Assisted by the reflection of FBG, refractive index (RI) measurement can be achieved by monitoring the peak power variation of the reflected FBG spectrum. By selecting different length of the no core fiber and center wavelength of the FBG, independent dual-point refractometer is easily realized. Experiment results show that the refractometer has a nonlinear relationship between the surrounding refractive index (SRI) and the peak power of the reflected FBG spectrum in the RI range of 1.3330–1.4086. Linear relationship can be approximately obtained by dividing the measuring range into 1.3330–1.3611 and 1.3764–1.4086. In the RI range of 1.3764–1.4086, the two sensing points have higher RI sensitivities of 319.34 dB/RIU and 211.84 dB/RIU, respectively.

1. Introduction

Optical fiber refractive index (RI) sensors have potential applications in food, chemical, and biological industries due to their intrinsic advantages of high sensitivity, compact size, remote sensing, immunity to electromagnetic interference and low cost. All-fiber RI sensors have been extensively investigated and realized in many different methods, such as fiber Bragg gratings (FBGs) [1,2], long period fiber gratings (LPFGs) [3,4], optical fiber coil resonators [5,6], microstructure based intermodal interferometers [7–9], Mach-Zehnder interferometers (MZIs) [10,11], Fabry-Perot interferometers (FPIs) [12,13], bent-fiber based interferometers [14,15], and multimode interferometers [16,17]. Recently, no-core fiber (NCF) based multimode interferometers have been thoroughly researched for RI measurement [18–20]. The key sensing element is constructed by splicing a section of NCF between two single mode fibers (SMFs) to form SMF-NCF-SMF (SNS) structure, which is easy to be fabricated and low cost. The NCF in the SNS structure uses surrounding media as its cladding; therefore multimode interference (MMI) effect in the NCF is easy to be influenced by the surrounding refractive index (SRI). Based on the wavelength modulation systems, the RI measurement can be realized by monitoring the center wavelength shifts of the peaks or selected dips [18–20]. Assisted with the FBG reflection based on broadband light source, RI measurement could be realized by detecting the variation of the reflective optical power at the Bragg wavelength [21,22]. Compared with the wavelength demodulation system, cost-effective power detection system is more suitable for practical use. Moreover, reflective refractometers are suitable for remote sensing.

Additionally, the multiplexing capability of fiber sensors is recognized as one of their main advantages. The sensor array can significantly simplify the sensing system and simultaneously monitor multiple separated sensing points [23]. The most commonly used method for multiplexing is to connect separated sensing head one after another [24–26]. As a result, the cascaded structures exhibit overlaps transmission or reflection spectra with multiple peaks or dips, which individually correspond to the separated sensing head. Although the cascaded structure is simple, but the cascaded fabrication processes are difficult to be controlled in order to locate the resonance wavelengths at different spectral positions. Furthermore, in the multiplexed sensing system based on transmission spectra, any damage of an individual sensing head will make the system not working properly, which is a major disadvantage of the cascaded structure.

In this paper, we propose and experimentally demonstrate a novel dual-point reflective fiber-optic refractometer based on MMI effect and FBG reflection. Each point consists of a SNS structure cascaded with a FBG. Assisted by the reflection of FBG, the wavelength modulation is

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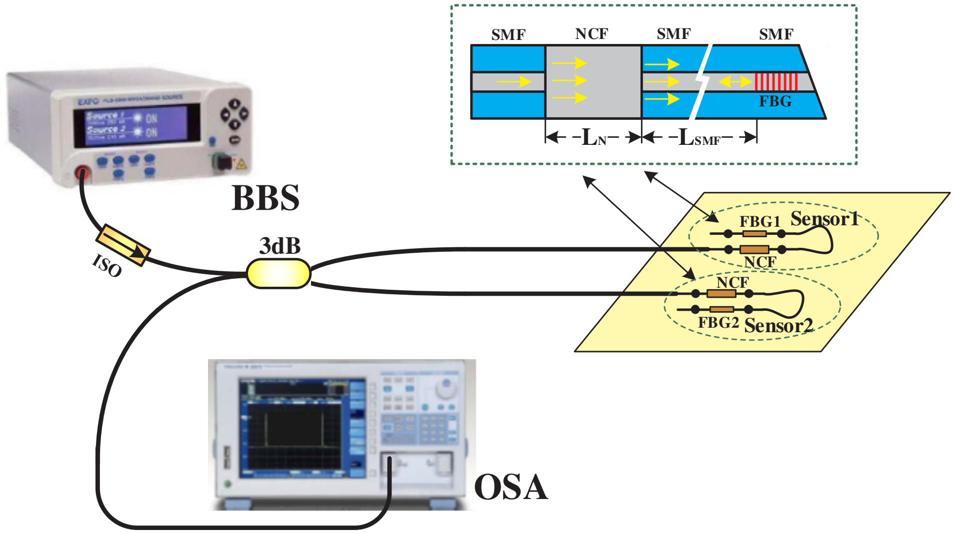

Fig. 1. Experiment setup of the proposed dual-point reflective RI sensing system.

converted into intensity modulation. The dual-point reflective fiber-optic refractometer adopts parallel structure, which has many distinctive advantages, such as simple multiplexed construction, easy fabrication of sensing head, reflective operation and cost-effective power detection. Compared with the aforementioned multi-point fiber optic refractometers with cascaded structures, every sensing point in the proposed refractometer can work independently and the damage of one sensing point doesn't have any influence on the other one. Moreover, the parallel structure is easy to add new sensing points, which makes it a good candidate for multi-point and remote RI measurement.

2. Principle and experiment setup

The schematic diagram of the sensing head is depicted in the dashed box of Fig. 1. The sensing head is constructed by a SNS structure cascaded with a FBG. L$_N$ is the length of the NCF, and L$_{SMF}$ is the distance between the NCF and FBG. When the input light is coupled from the lead-in SMF into the NCF, the high-order modes will be excited and transmit within the NCF, which is sensitive to the SRI. Owing to the self-imaging effect in the NCF, the SNS structure acts as an optical bandpass filter (BPF) whose transmission spectrum is determined by the SRI. The transmission spectrum of the BPF is then reflected by the FBG whose center wavelength is insensitive to the SRI. Compared with the previous reports [21,22], the distance L$_{SMF}$ in our experiment needn't to be restricted to several millimeters and it should be long enough to eliminate the cladding modes because the cladding mode reflections would not be useful in our measurements. It is worth noting that, in order to improve the measurement accuracy, the ultimate end of the sensor should be cleaved at an angle so as to eliminate the facet reflection. The reflection spectrum of the FBG is filtered by the BPF again. Therefore, the peak power of the reflected FBG spectrum is modulated by the transmission spectrum of the SNS structure. Through measuring the peak power variation of the reflected FBG spectrum, the SRI information can be determined.

Assuming the fusion process is ideal, only the linear polarization LP_{0m} modes can be excited and transmit in the NCF section [17]. By defining the field profile of LP_{0m} mode as $\Psi_m(r)$, the input electric field of the NCF can be expressed as

$$E(r,0)=\sum_{m=1}^{M} c_m\Psi_m(r) \tag{1}$$

where c_m is the excitation coefficient of each LP_{0m} mode. When the light propagates in the NCF, the field distribution at the distance z can be written as

$$E(r,z)=\sum_{m=1}^{M} c_m\Psi_m(r)\exp(j\beta_m z) \tag{2}$$

where β_m is the longitudinal propagation constant of the LP_{0m} mode. Then the transmittance of the SNS structure can be calculated by

$$T=10\log_{10}\{\sum_{m=1}^{M}\sum_{n=1}^{M} c_m c_n^*\Psi_m(r)\Psi_n^*(r)\exp[j(\beta_m-\beta_n)z]\} \tag{3}$$

The difference between the longitudinal propagation constants of the m and n order mode can be expressed as

$$\beta_m-\beta_n=\frac{u_m^2-u_n^2}{2ka_{NCF}^2 n_{NCF}} \tag{4}$$

where k is the wave number, a_{NCF} is the radius of the NCF, n_{NCF} is the effective RI of the fundamental mode of the NCF, u_m and u_n are the normalized transverse wave number and can be approximated by $u_m=\pi(m-1/4)$ and $u_n=\pi(n-1/4)$, respectively. When the phase difference between the two modes equals to the integer multiple of 2π, constructive interference between these two modes occurs. In the SNS structure, the surrounding media acts as the cladding of the NCF. As the SRI changes, the effective RIs of the LP_{0m} modes vary accordingly, which results in the changes of the excitation coefficient of each LP_{0m} mode. Ultimately, the transmission spectrum of the BPF will shift with the variations of SRI. The peak wavelength of the transmission spectrum can be calculated by [27]

$$\lambda_0=\frac{pn_{NCF}D_{NCF}^2}{L_N} \tag{5}$$

where p is the self-image number, L_N is the length of the NCF, and D_{NCF} is the effective diameter of the fundamental mode. When the SRI increases, the effective RI of the fundamental mode is increased because the evanescent filed penetrates more into the surrounding media. This also leads to the increase of the effective diameter of the fundamental mode owing to the reduction of the RI difference between the core and cladding. Therefore, according to the above equation, the peak wavelength of the BPF has a red shift when the SRI increases.

The proposed dual-point reflective RI sensing system is established according to the configuration shown in Fig. 1. The light from a broadband optical source (BBS) is divided into two parts by a 2 × 2 3-dB optical coupler. A dual-stage optical isolator (ISO) is inserted to avoid any damage from the reflection signals. Each output port is connected with a sensing head named sensor 1 and sensor 2. The reflection spectrum is monitored by an optical spectrum analyzer (OSA,