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Intensity-modulated refractive index sensor with anti-light source fluctuation based on no-core fiber filter

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ABSTRACT

A differential intensity-modulated refractive index (RI) sensor consisting of a no-core fiber (NCF) filter, a circulator and two fiber Bragg gratings (FBGs) is proposed and demonstrated. A section of the NCF is sandwiched between two parts of single mode fibers (SMFs) to form a band-pass filter. The Bragg wavelengths of the FBGs are chosen at the two edges of the filter, respectively. The peak wavelength of the NCF filter has a red-shift with the increase of the surrounding refractive index (SRI) while the Bragg wavelengths have no change, which results in the variation of the difference of the two FBGs reflective intensities, thus the differential intensity modulation to the SRI can be accomplished. Compared with directly connecting the NCF filter and the FBGs, this sensing structure can increase the output power so as to improve the measuring resolution. The experimental results show that the RI sensitivities are −99.191 dB/RIU and −139.958 dB/RIU at the range of 1.3329–1.3781 and 1.3781–1.401, respectively. In addition, the disturbance from the light source fluctuation and temperature cross sensitivity can be minimized effectively, which has great potential in actual applications.

1. Introduction

Fiber optic RI sensors have been reported in a diverse range of food processing, pharmaceutical and bio-chemical measurements fields based on FBG [1,2], long period fiber grating (LPFG) [3,4], Fabry-Perot interference (FPI) [5,6], Mach-Zehnder interference (MZI) [7,8], Michelson interference (MI) [9,10], Sagnac interference [11] and multimode interference (MMI) [12–16]. Among them, the MMIs based on the NCF show great convenience in applications owing to its compact structure, ultrahigh sensitivity and high reproducibility [13–15]. A section of NCF is spliced between a segment of input and output SMF to form a SMF-NCF-SMF (SNS) structure, which is extremely sensitive to the SRI because the surrounding media acts as the cladding of the NCF. Recently, most of the previous papers which reported the SNS structure have focused on the wavelength modulation [13] and absolute intensity modulation [14–16]. As for the former, the shift of peak or dip wavelength is monitored by the expensive wavelength demodulation instruments like optical spectrum analyzer (OSA), which restricts its applications. The cost-effective intensity modulation is more suitable for the practical use compared to the wavelength modulation method. In Ref. [14], a SMF-etched multimode fiber (MMF)-SMF structure is presented during hydrofluoric (HF) acid etching process. The diameter of the etched MMF and the etching time are controlled to achieve the maximum RI sensitivity of about 46 dB/RIU in the range of 1.333–1.45. However, the etching process leads to poor repeatability and low sensitivity. In Ref. [15], a SNS structure cascaded with a FBG is proposed to measure the SRIs through both wavelength and power of each FBG reflected mode. The distance between the SNS structure and the FBG is only 6 mm to generate the FBG cladding reflected modes, which limits the use of the low-cost power meter because the wavelength spacing between the FBG cladding and core reflected mode is less than 5 nm. Furthermore, the light source fluctuation and fiber attenuation are not taken into consideration as for the absolute intensity modulation method, which reduces the measuring accuracy.

In this letter, a novel intensity-modulated RI sensor based on a SNS structure, a circulator and two cascaded FBGs namely SNSCFF structure is proposed and demonstrated. The SNS structure is regarded as a band pass filter (BPF) by choosing the proper diameter and length of the NCF. The Bragg wavelengths of the two FBGs are selected at the two linear regions of the NCF filter. The light filtered by the NCF filter is reflected by the two FBGs via the circulator and then transmits back to the circulator instead of being filtered by the NCF filter again so as to obtain higher output intensity. As the SRI increases, the peak wavelength of the NCF filter has a red-shift

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while the Bragg wavelengths of the FBGs keep unchanged, which results in the intensities at the two FBGs change in the opposite trend. Therefore, the differential reflective intensity changes as the SRI varies. In addition, the RI sensitivity of the reflective intensity difference is higher than that of any single reflective intensity of FBGs. Moreover, the impacts of light source fluctuation, fiber attenuation and temperature cross sensitivity are minimized by calculating the reflective intensity difference of the two FBGs. This sensor possesses the merits of simple fabrication, high reproducibility, differential intensity modulation, anti-light source fluctuation, and temperature self-compensation, which makes significant directive role in the engineering applications.

2. Principle and fabrication

The schematic diagram of the sensing head is shown in the dashed box of Fig. 1. A section of NCF is sandwiched between the input and output SMF to form a SNS structure, and a circulator is spliced between the SNS and two cascaded FBGs to form a SNSCFF structure. When light is injected from the input SMF into the NCF, multiple high order modes of the NCF, i.e. LP_{0m}, are excited from the fundamental mode LP_{01} due to the core-diameter mismatch and propagate along the NCF where multimode interference effect occurs. At the other splicing point, the high order modes are coupled back to the core mode of the output SMF. The SNS structure can be regarded as a BPF by choosing the proper diameter and length of the NCF, whose peak wavelength is expressed as [14,15]

$$\lambda = \frac{p n_{NCF} D_{NCF}^2}{L_{NCF}} \tag{1}$$

where p is the number of the self-image period, n_{NCF} and D_{NCF} correspond to the effective RI and diameter of the fundamental mode in the NCF, L_{NCF} is the length of the NCF. The fourth self-image period (and multiples) is used because of the narrowest spectra bandwidth and minimum insertion losses [17]. The transmission spectrum of the NCF filter is like a triangular, and the Bragg wavelengths of FBG_1 and FBG_2 are selected in the two linear edges of the filter, respectively. The output light filtered by the NCF filter is reflected by the two cascaded FBGs via a circulator and then transmitted back to the circulator.

The sensing principle is expressed as follows. As the SRI increases, the RI difference between the core and cladding is reduced, then the effective RI of the NCF increases because of the Goos–Hänchen shift [18], and the effective diameter of the NCF increases since the evanescent filed penetrates more into the liquid. Therefore, the peak wavelength of the SNS filter will shift to the longer wavelength while the Bragg wavelength keeps unchanged. In addition, the two slopes of the transmission spectrum of the NCF filter are opposite, thus the reflection intensities of the two FBGs change in the opposite trend. Their intensity difference is more sensitive to the SRI than any of the single reflective intensity of the FBGs, which can be written as [19]

$$\begin{aligned} \Delta I = I_1 - I_2 &= \int_{-\infty}^{+\infty} S(\lambda)\cdot T_1(\lambda-\Delta\lambda)\cdot R_1\cdot\delta(\lambda-\lambda_1)d\lambda \\ &\quad - \int_{-\infty}^{+\infty} S(\lambda)\cdot T_2(\lambda-\Delta\lambda)\cdot R_2\cdot\delta(\lambda-\lambda_2)d\lambda \\ &= R_1 S(\lambda_1)T_1(\lambda_1-\Delta\lambda) - R_2 S(\lambda_2)T_2(\lambda_2-\Delta\lambda) \end{aligned} \tag{2}$$

where ΔI is the differential intensity of the two FBGs, I_1 and I_2 are the reflective intensities of the FBG_1 and FBG_2, $S(\lambda)$ is the power spectral density (PSD) function of light source, $T_1(\lambda)$ and $T_2(\lambda)$ are the initial transmission spectrum functions of the two linear regions of the NCF filter, λ_1 and λ_2 are the Bragg wavelengths of FBG_1 and FBG_2, $\Delta\lambda$ is the wavelength shift of the spectrum of the NCF filter induced by the change of the SRI, R_1 and R_2 are the reflective coefficients of the FBG_1 and FBG_2, $\delta()$ is the unit impulse function, $R_1\delta(\lambda-\lambda_1)$ and $R_2\delta(\lambda-\lambda_2)$ are the reflective spectrum functions of the FBGs which are described as impulse functions because the bandwidths of the FBGs are far smaller than that of the NCF filter. Because the $\Delta\lambda$ is related to the SRI, the SRI measurement can be accomplished by calculating the differential intensities of the two FBGs. Besides, the NCF filter and FBGs both shift to the longer wavelength with the similar temperature sensitivities as the temperature increases [13], which results in the advantage of minimal temperature dependence for the RI measurement. Furthermore, due to the fact that the reflective intensities of the two FBGs change in the same trend when the intensity of the light source varies or the transmission distance changes, the intensity error from the fluctuation of the light source and fiber attenuation are eliminated by differential intensity modulation. Finally, because the reflective light of the two FBGs transmits back to the circulator directly compared with a SNS-FBG-FBG (SNSFF) structure which is filtered by the NCF filter twice, the reflective intensities increase significantly, which is more suitable for engineering applications with low-cost light source module.

The experimental setup is shown in Fig. 1. A broadband source (BBS, ZLS-1545-010-1-2-D, Zewda) is used to illuminate the sensing head, an optical spectrum analyzer (OSA, AQ6370B, Yokogawa, wavelength resolution: 0.02 nm) is used to record the variations of the spectra from the 1% port of a 1:99 optical coupler for auxiliary experiment, the other output light from the 99% of the coupler is filtered by a wavelength division multiplexer (WDM) to separate the reflective light of the two FBGs. The intensities of FBG_1 and FBG_2 are monitored by the optical power meter (OPM, AV6334) through the second port and third port of the WDM, respectively. The NCF filter and the two FBGs are parallel fixed on the tempered glass by the UV glue to ensure the similar thermal expansion coef-

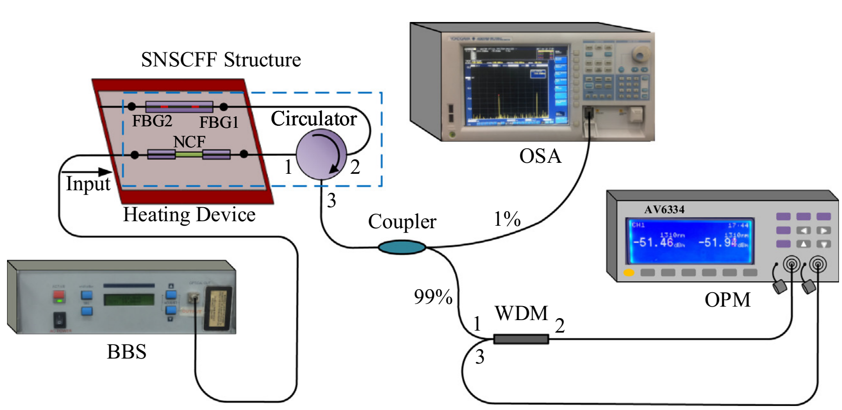

Fig. 1. Scheme of the experimental setup.