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Power-referenced refractometer based on hybrid fiber grating

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ABSTRACT

A power-referenced fiber refractometer based on a hybrid fiber grating formed by a tilted-fiber Bragg grating (TFBG) cascading by a chirped-fiber Bragg grating (CFBG) is proposed and experimentally demonstrated. The optical signal reflected by the CFBG passes twice through the TFBG that enhances sensitivity of the refractometer. In addition, the optical signal is propagating all the way in the fiber core so that the extra insertion loss is low. Refractive index measurement with sensitivity up to 597.2 $\mu\text{W}/\text{R.I.U.}$ is achieved within the range from 1.333 to ~ 1.42 . The maximum detectable refractive index is ~ 1.45 .

Keywords: Refractometers, optical fiber sensors, tilted-fiber Bragg gratings (TFBGs), chirped-fiber Bragg gratings (CFBGs)

1. INTRODUCTION

Optical fiber based refractometers have been widely investigated and used in many areas ranging from biomedical measurements to environmental monitoring due to their many advantages including small size, light weight, safe operating in hazardous environments, immunity to electromagnetic interference, and high sensitivity [1-14]. Most of them are based on the interaction between surrounding refractive index and evanescent field of light propagating inside special fibers or fiber devices, such as side-polished fibers, cladding-etched fibers, long-period gratings (LPGs) [4-6] and tilted-fiber Bragg gratings (TFBGs) [7-11]. Recently, TFBGs have received lots of attentions due to its high sensitivity to surrounding refractive index from both wavelength and intensity of cladding mode resonances. However, TFBG refractometers based on wavelength shift measurement need complex wavelength interrogation units [8]. Power-referenced TFBG refractometers by measuring the transmission power of TFBG are inconvenient in practical applications [10]. An improved design to change the transmission operation mode into reflection is by employing an offset splicing or fiber taper in front of the TFBG to recouple the backforward-propagating cladding modes into the backforward-propagating core mode [11, 15]. However, the mode coupling structures in these reflection mode designs weaken the fiber strength and introduces high insertion loss that reduce the signal power seriously.

In this work, an alternative power-referenced optical fiber refractometer operating in reflection mode is proposed by using a TFBG cascaded by a reflection-band-matched chirped-fiber Bragg grating (CFBG). The optical signal reflected by the CFBG passes twice through the TFBG that enhances the measurement sensitivity significantly. What's more, the optical signal is propagating all the way in the fiber core so that the extra insertion loss is low and the good fiber strength is maintained.

Fig. 1 (a) Transmission spectrum of the TFBG; (b) Transmission and reflection spectra of the CFBG; (c) Reflection spectrum of the CFBG-cascaded TFBG.

Fig. 2 Experimental setup for surrounding refractive index measurement.

2. SENSOR FABRICATION AND PRINCIPLE

In the experiment, both the TFBG and the CFBG were manufactured by using phase mask method in a hydrogen-loaded Germanium-doped single-mode fiber with a frequency-doubled Argon laser emitting at 244 nm. The TFBG, achieved with a uniform phase mask of 1083 nm period, is 10-mm long with a tilt angle of 6° . Its Bragg mode resonance locates at 1578 nm with transmission loss of ~ 0.5 dB and the cladding mode resonances locate between 1500 to 1576 nm. The CFBG is 18-mm long, with reflectivity of 9.5 dB in a broad and well-designed reflection band of ~ 36 nm (1528-1564 nm), which covers most of the cladding mode resonance region of the TFBG. Figure 1 (a) and (b) show the measured optical spectra of the TFBG and the CFBG, respectively. After the TFBG was cascaded by the CFBG, the reflection spectrum was measured and shown in Fig. 1(c). It can be seen that intensity of the reflected Bragg mode is much lower than that of the cladding modes so that it can be neglected in the measurement.

The TFBG has tilted grating planes related to the perpendicular of the fiber axis. It can not only couple the light from forward propagating core mode to backward propagating cladding modes [16,17]. What's more, the effective refractive indices and the mode coupling coefficient for the later one are dependent on the refractive index of the ambient material. When the surrounding refractive index approaches effective refractive index of a guided cladding mode, the resonance will be shifted in wavelength as the effective index is modulated by the ambient material firstly [8]. And when surrounding refractive index reaches the effective refractive index, the resonance stops shifting in wavelength but then starts to decrease in amplitude as the mode becomes lossy (it is no longer totally internally reflected by the cladding boundary as its evanescent field penetrates more and more into the surrounding liquid) [16]. Spectrally, this behavior is marked by a smoothing of the cladding mode resonances and reduction of the transmitted optical power.

By cascading the reflection-band-matched CFBG to the TFBG, the operation mode of the refractometer is changed from transmission to reflection that makes the lead-in and lead-out optical fiber the same one, providing obvious convenience in practical applications. In addition, the light passes through and is modulated twice by the TFBG that contributes to improve the sensitivity.

Fig. 3 Transmission spectral evolution of the TFBG (a) and reflection spectral evolution of the refractometer (b) under various refractive indices.

3. EXPERIMENTAL RESULT AND DISCUSSIONS

The experimental setup for surrounding refractive index measurement with the proposed refractometer is shown in Fig. 2. Light from a broadband source (BBS) centered at wavelength of 1550 nm was launched into the gratings through an optical fiber circulator. The reflected light is measured by using an optical spectrum analyzer (OSA, AQ6370) or an optical power meter (OPM). The gratings were kept free from any strain and bending. The TFBG was surrounded by glycerin-water solution whose refractive index can be changed by varying the doping concentration.

When surrounding refractive index reaches or exceeds effective refractive index of a cladding mode, it is no longer guided and converted into a continuum of radiation mode. Fig. 3(a) shows the measured transmission spectra of the TFBG when surrounding refractive index is increased. The cladding mode resonances become attenuated and disappear gradually from the short wavelength because high-order cladding modes have relatively low effective refractive index and thus are influenced by surrounding refractive index and transferred into radiation modes first. It can also be found that the transmission optical power of the TFBG decreases obviously with the mode transformation that can be measured in the reflection method by cascading the reflection-band-matched CFBG. Evolution of the reflection spectra by the TFBG cascaded by the CFBG is shown in Fig. 3(b). It can be seen that only the cladding mode resonance modulated wavelength region is selected in the reflection spectra that helps us achieve high signal-to-noise ratio. The reflected optical power is reduced as expected and the loss introduced by the continuum radiation mode is nearly doubled when compared with that in the transmission spectra. And this helps to improve sensitivity of the refractometer in a certain extent.

Figure 4 shows the measured results of reflected optical signal power against surrounding refractive index within the range from 1.333 to 1.474. It can be seen that the reflected optical power decreases rapidly and linearly with refractive index at low value then decreases less rapidly for intermediate value and tends to a fixed power of $\sim 92 \mu\text{W}$ at high value. The nonlinear response is caused by the nonuniform loss with wavelength of the TFBG when the cladding mode resonances are converted into radiation mode. It can be seen in Fig. 3(b) that the radiation mode introduced loss is relatively large and uniform, ranging from 6.5 dB to 8.0 dB, from the short wavelength side to the middle, and it decreases gradually to about only 1 dB from the middle to the long wavelength side. The reduced loss of radiation mode leads to reduced variation in optical signal power that in turn results in tending to a fixed power. The achieved sensitivity to surrounding refractive index is $597.2 \mu\text{W}/\text{R.I.U}$ within the linear response range from 1.333 to ~ 1.42 . The linearity is good with the R-squared value of 0.9983. The sensitivity becomes smaller gradually till no response due to the limited measurement. The maximum detectable refractive index is ~ 1.45 , which is close to the refractive index of the fiber cladding.

Fig. 4 Reflected optical power against surrounding refractive index.

Besides the power-referenced measurement method, the proposed refractometer possesses several other advantages. The optical signal propagates all the way in the fiber core that introduces nearly no extra insertion except for the reflection loss caused by the CFBG. There is no cladding mode recoupling structure such as off-set fusion splice or fiber taper involved so that the good fiber strength is retained. By cascading the CFBG to the TFBG, the optical signal is modulated twice by the TFBG thus the measurement sensitivity is improved. Meanwhile, the refractometer can work in reflection method which is more convenient than the transmission operation mode in some practical applications. There are also some drawbacks including the relatively low response and small linear measurement range, but the performance can be improved by using a light source with higher output power and/or using a CFBG with wider reflection band and higher reflectivity.

4. CONCLUSION

A power-referenced refractometer is reported based on a hybrid fiber grating formed by a TFBG cascading by a reflection-band-matched CFBG. The optical signal reflected by the CFBG passes twice through the TFBG that enhances sensitivity of the refractometer significantly. In addition, the optical signal is propagating all the way in the fiber core so that the extra insertion loss is low and the fiber strength is maintained. Refractive index measurement with sensitivity up to 597.2 $\mu\text{W/R.I.U.}$ is achieved within the range from 1.333 to ~ 1.42 . The maximum detectable refractive index is ~ 1.45 . The proposed power-referenced fiber refractometer possesses advantages of robustness, low cost, easy fabrication and convenient operation in practical applications.

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