RESOLUTION-IMPROVED REFRACTIVE INDEX SENSING SYSTEM BASED ON MICROWAVE PHOTONICS FILTER AND MICROFIBER GRATTING

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ABSTRACT

A novel refractive index (RI) sensing system with improved resolution based on a microwave photonics filter (MPF) is proposed and experimentally demonstrated. The sensing probe used for RI measurement is a microfiber Bragg grating. We use the frequency interrogation scheme (different from the traditional wavelength demodulation method) for resolution improvement of RI detection. The frequency shift of MPF notch point shows a linear relationship with the surrounding RI change over the range of 1.33 to 1.38 and a RI sensing resolution of 2.63×10^{-5} RIU has been achieved experimentally. The proposed MPF based RI sensing system provides a new interrogation method over the frequency domain with improved RI sensing resolution, as a good candidate for rapid and highly sensitive detection in chemical and environmental monitoring.

Keywords: *Refractive index, microwave photonic filters, micro fiber grating*

1. INTRODUCTION

Refractive index (RI) is an important parameter in biotechnological and chemical industries [1]. All-fiber RI sensors have been widely used due to their distinct advantages such as high sensitivity, compact size and immunity to electromagnetic interference. Traditional ways that have been demonstrated in RI measurement include long period fiber gratings (LPFGs), tilted fiber Bragg gratings (TFBGs), Fabry-Perot interferometry, fiber surface plasma resonance (SPR) technology and fiber taper technology [2-7]. Recently, microfiber Bragg grating (mFBG) has been proposed and rapidly developed in RI measurement [8, 9]. It extremely decreases the sensor device in size and provides strong evanescent fields out of fiber cladding. Since most of the traditional spectra monitor-based RI sensors are wavelength-encoded, an optical spectrum analyzer (OSA) and a broadband light source are needed to detect the wavelength shift. However, traditional wavelength demodulation methods suffer from the problems such as polarization fading and reliability in crucial environment.

With the development of communication networks and photonic technology, the microwave photonic signal processing has become more convenient and effective. Microwave photonic filter (MPF) is a powerful technique to process microwave signals directly in the optical domain [10-12]. Besides the known radio over fiber (RoF) system and military phased array radar, MPF has a potential application in radio astronomy and Terahertz wave technologies. Owing to its fast signal processing speed, MPF has started to attract research attentions in sensing domain.

In this paper, we propose and demonstrate a novel RI sensing system with improved resolution based on a MPF. The RI sensing component is an mFBG functioning as an optical bandpass filter in MPF. The proposed RI sensing system has the advantages of higher sensing resolution and higher Q value compared with traditional wavelength-encoded RI sensors, and shows a well performance in RI measurement.

2. EXPERIMENT SETUP AND PRINCIPLE

2.1 Experimental set up

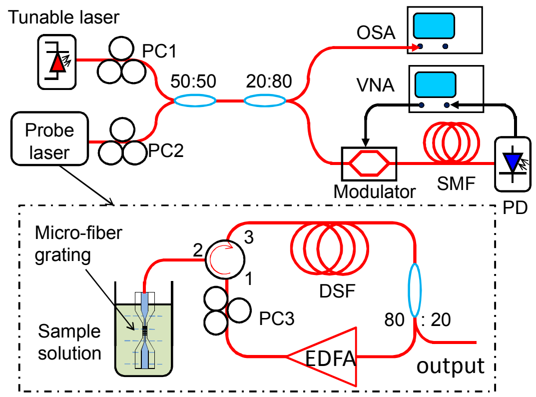

Fig.1. The experimental setup of MPF based bio-sensing system

Fig.1 shows the arrangement of the proposed MPF based RI sensing interrogation scheme. The optical source of the MPF consists of a probe laser from an erbium-doped fiber ring laser (EDFL) and a reference laser generated by a tunable laser. As shown in the dotted box, the mFBG in the EDFL ring cavity functions as a narrow bandwidth optical filter to select wavelength. Only the longitudinal modes around the peak of mFBG reflective spectra (fundamental mode peak) can lase out. A polarization controller (PC3) is used to optimize polarization state. In order to increase the cavity length and to stabilize the output of the probe

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laser, a 660 meters length of dispersion shifted fiber (DSF) was placed inside the ring cavity. The probe laser and the reference laser (1548.844 nm) are coupled to one route as the optical source of MPF.

80% of the optical source is used as carrier wave and other 20% part is sent to an OSA for wavelength shift monitoring. The RF signal was modulated to the carrier wave by an intensity modulator and another 2 PCs (PC1 and PC2) are used before the intensity modulator for optimum modulation performance. The modulated signals are launched into a 10-km long single mode fiber (SMF) acting as a wideband dispersive medium and finally detected by a photodetector (PD). The calibrated frequency response of the MPF system is measured by a vector network analyzer (VNA).

The micro fiber was a commercial multimode fiber (MMF) drawn and tapered with a butane flame brushing. The mFBG was inscribed by 193 nm excimer laser and phase mask method. The reflective spectra of mFBG in the air and pure water are shown in Fig. 2.

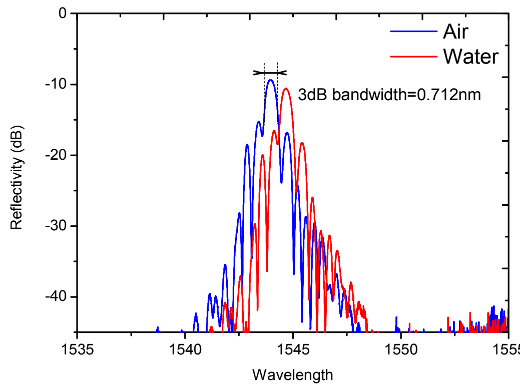

Fig.2. The reflective spectra of mFBG in air (blue curve) and pure water (red curve).

The mFBG we used has a large 3dB bandwidth (0.712 nm) and some side lobes exist around the peak wavelength. The character of mFBG is insignificant, for the MPF based sensing system doesn't rely on the performance of sensor probe.

2.2 Operation principle

The calibrated frequency response of the MPF based RI system can be expressed as

$$H(f)=\left|r(A_p+A_r e^{-i2\pi f\Delta T})\right|, \quad (1)$$

where $\Delta T=DL(\lambda_r-\lambda_p)$ is the time delay between the probe tap and the reference tap, λ_p and λ_r are the wavelength of probe laser and reference laser respectively. A_p and A_r are the tap values of probe laser and reference laser. D=17ps/km/nm is the dispersion coefficient around 1550nm, L is the length of the SMF and r is the normalization coefficient. The free spectrum range (FSR) of the MPF is

$$FSR=\frac{1}{\Delta T}=\frac{1}{(\lambda_r-\lambda_p)\cdot D\cdot L}=\frac{1}{\Delta\lambda\cdot D\cdot L}, \quad (2)$$

where $\Delta\lambda=\lambda_r-\lambda_p$ is the initial wavelength interval between probe laser and reference laser.

The alteration of ambient RI will affect the evanescent filed distribution and lead to the wavelength shifting of probe laser. The differential of *FSR* can be expressed as

$$d(FSR)=-\frac{d(\Delta\lambda)}{(\Delta\lambda)^2\cdot D\cdot L}=\frac{d\lambda_p}{(\Delta\lambda)^2\cdot D\cdot L}, \quad (3)$$

where $d\lambda_p$ is the differential of λ_p and $d(\Delta\lambda)=-d\lambda_p$ due to the fixation of λ_r. $dFSR$ is linearly related to $\Delta\lambda_p$ when the λ_r is fixed. *FSR* is achieved by measuring the frequency of notch point. The frequency of the n-th notch point is

$$f_{notch}(\mathrm{n})=(\mathrm{n}-0.5)FSR=\frac{(\mathrm{n}-0.5)}{\Delta\lambda\cdot D\cdot L}. \quad (4)$$

Higher sensitivity can be achieved by measuring the frequency shift of higher ordinal notch. We chose the frequency point of 6-th notch as sensing parameter.

3. RESULT AND DISCUSSION

3.1 High RI resolution

The change of surrounding RI is achieved by adjusting the concentration of sodium chloride solution. The RI range of the aqueous solutions is from 1.335 to 1.375. The RI sensing characteristics of probe laser monitoring and MPF based sensing system are shown in Fig.3.

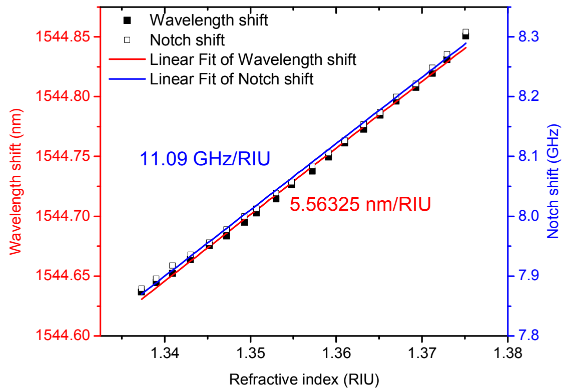

Fig.3. Sensitivity of surrounding RI measurement for probe laser (red curve) monitoring and MPF sensing system (blue curve).

The RI sensitivity of MPF system is 11.9 GHz/RIU. The comparison of RI sensing resolution between probe laser monitoring and MPF sensing system is shown in Tab.1

	Wavelength shift of probe laser	Frequency shift of 6-th notch
Sensitivity	5.56325 nm/RIU	11.9 GHz/RIU
Analyzer resolution	0.0038 nm	312500 Hz
Sensing resolution	$6.83e^{-4}$ RIU	$2.63e^{-5}$ RIU

Tab.1. Sensing resolution of surrounding RI measurement for probe laser monitoring and MPF sensing system

The RI resolution of MPF sensing system is about one order of magnitude higher than that of probe laser monitoring method. The sensitivity and resolution of MPF sensing system can be further improved by measuring the frequency shift of higher order notch and utilizing higher VNA detecting resolution respectively.

3.2 High Q value

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The probe laser monitoring spectra and frequency responses of the MPF based RI system (when RI is 1.339, 1.3507, 1.3632 and 1.3751) are shown in Fig.4.

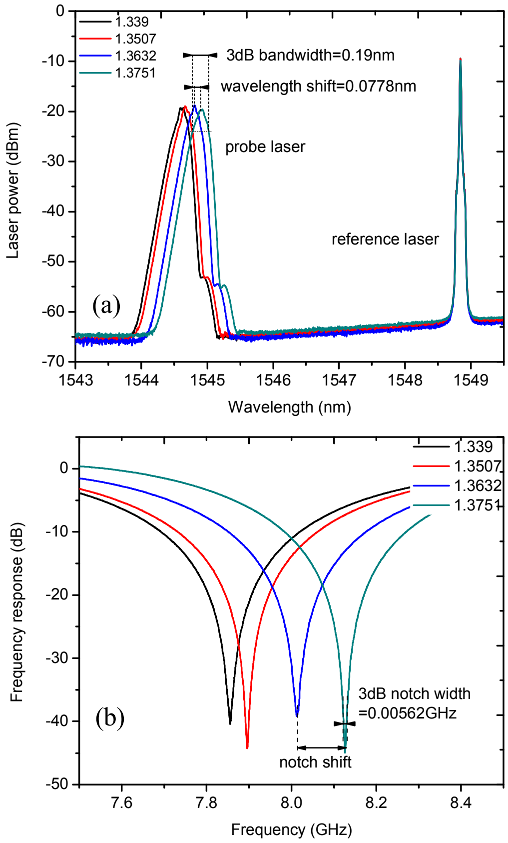

Fig.4. (a) Wavelength shifts of probe laser. (b) Frequency shifts of the 6-th notch under different surrounding RI.

An overlapping area exists among laser spectra under different surrounding RI which does not occur in MPF sensing process. The Q value namely the ratio of shift amount to the 3 dB bandwidth is an important parameter to represent sensing identification ability. The comparison of Q values for probe laser monitoring and MPF sensing system (from RI=1.3632 to 1.3751) are shown in Tab.2.

	wavelength shift of probe laser	frequency shift of 6-th notch
Shift amount	0.0778 nm	0.1549 GHz
3 dB bandwidth	0.19 nm	0.00562 GHz
Q value	0.41	27.6

Tab.2. Comparison of Q values for probe laser monitoring and MPF based sensing system (from RI=1.3632 to 1.3751).

The MPF sensing system has a much higher Q value than the laser spectra monitoring method. It should also be noticed that for traditional spectra monitor method in which only the passive component spectra are measured, the Q value is even lower than the probe laser monitoring method owing to a larger 3 dB bandwidth (as shown in Fig.2).

4. CONCLUSION

We proposed and demonstrated a novel RI sensing system with improved resolution based on a MPF. The mFBG is the RI sensing probe and also a component of the MPF system. The MPF based RI sensing system has a high sensing resolution of $2.63e^{-5}$ RIU and higher Q value compared with traditional spectra monitoring methods, and shows a great RI sensing characteristic.

6. ACKNOWLEDGMENTS

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