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Refractive index sensor based on θ -shaped microfiber resonator and Vernier effect

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ABSTRACT

A compact refractive index (RI) sensing probe with controllable sensitivities based on a θ -shaped microfiber resonator and Vernier effect is reported. By cascading the θ -shaped microfiber resonator with a fiber Fabry-Perot interferometer, Vernier effect is generated to enhance the RI sensitivity. Both theoretical analyses and experimental results demonstrate that the RI sensitivity can be tuned by changing the cavity length of the θ -shaped microfiber resonator. The RI sensitivity is widely tuned from 311.77nm/RIU to 2460.07nm/RIU in the experiment. The θ -shaped microfiber resonator and the proposed method of generating Vernier effect could find important applications in optical fiber sensing field.

Keywords: Fiber optics sensors, refractive index sensing, microfiber, micro-optical devices

1. INTRODUCTION

Due to their important roles in biochemical fields, sensitive optical refractive index (RI) detectors with small footprint has been intensively investigated [1, 2]. With unique advantages of small size, great flexibility and high fraction of evanescent field, microfiber has become an excellent medium of constructing miniature RI sensors [3]. Plentiful microfiber based refractometers with diverse sensing schemes, such as microfiber gratings and microfiber based in-line interferometers, were developed in the past years [4-6]. But the disadvantages of complicated fabrication processes, fragile structures, rough packaging and poor reconfigurability are obstacles to many practical applications. Besides, much effort has also been contributed to RI sensors based on microfiber resonators [7], but the sensitivities are usually not high enough.

Vernier effect attracts great interest from the optical sensing field because of its capability to substantially enhance the measuring sensitivity [8]. Vernier effect induced by two cascaded silicon micro-ring resonator has been abundantly studied for RI detection. But the high cost and the incompatibility with fiber devices limit their applications in existing fiber systems.

In this paper, we propose a sensitivity-controllable RI probe based on a θ -shaped microfiber resonator and a fiber Fabry-Perot interferometer (FFPI). The θ -shaped microfiber resonator is a specially designed reflective-type structure with intrinsic single mode fiber pigtail to directly connect with the fiber devices. By cascading it with a FFPI, Vernier effect can be generated to enhance the RI sensitivity. Both theoretical analyses and experimental results are presented to demonstrate the sensitivity controllability of the proposed RI sensors.

2. OPERATING PRINCIPLE

The schematic diagram of the proposed θ -shaped microfiber resonator is shown in Fig. 1(a). In the structure, the coupling efficiencies and coupling losses of two coupling areas I, II are (k_1, γ_1) and (k_2, γ_2) , respectively. In the following

discussion, we take $k_1 = k_2 = k$ and $\gamma_1 = \gamma_2 = \gamma$ for simplification. l_0, l_1 and l_2 are the distances from port 3 to port 6, from port 2 to port 5 and from port 7 to port 4, respectively. Because of the bridge section between the two coupling areas, the clockwise mode can be coupled into the counter clockwise mode, enabling the resonant light to be output as reflection through port 1. By using the transfer matrix theory, the function of the reflective output is obtained as:

$$r = j \cdot \exp[j\beta(l_1 + l_0)] \cdot (1 - \gamma)(1 - k)^{1/2} k^{1/2} \times \left\{ \begin{aligned} &2 \cdot (1 - \gamma)^{1/2} (1 - k)^{1/2} \frac{(1 - \gamma)(1 - k) \exp(j\beta L)}{[1 + (1 - \gamma)k \exp(j\beta L)]^2} + \\ &\frac{2(1 - \gamma)^{1/2} (1 - k)^{1/2}}{1 + (1 - \gamma)k \exp(j\beta L)} \end{aligned} \right\} \quad (1)$$

Here, β is the propagation constant in the θ structure, and $L = l_1 + l_2$ is the length of whole ellipse track of the θ -shaped cavity. Then the reflection intensity is $R = |r|^2$. By calculating Eq. (1), it shows that the reflection of the θ -shaped microfiber resonator exhibits comb spectrum, when the coupling strength is low (that is k is small and γ is high).

Figure 1. (a) The schematic diagram of the θ -shaped microfiber resonator; (b) The experimental setup for RI sensing (Inset: an experimentally fabricated θ -shaped microfiber resonator). BBS: broadband source; OSA: optical spectrum analyzer; FFPI: fiber Fabry-Perot interferometer

Since the illuminated light in the θ -shaped microfiber resonator has high proportional of evanescent field, change of the surrounding RI will result in the variation of the mode index, leading to the shift of the resonant wavelength. When the surrounding RI n_a is changed by Δn_a , the resonant wavelength of the θ -shaped microfiber resonator λ_1 can be shifted by:

$$\Delta \lambda_1 = \lambda_1 \left(\Delta n_a / n_{eff1} \right) \cdot \left(\Delta n_{eff1} / \Delta n_a \right) \quad (2)$$

where n_{eff1} and Δn_{eff1} are the effective RI of the θ -shaped microfiber resonator and its variation. Then the RI sensitivity of the θ -shaped microfiber resonator is expressed as:

$$S_1 = \Delta \lambda_1 / \Delta n_a = \left(\lambda_1 / n_{eff1} \right) \cdot \left(\Delta n_{eff1} / \Delta n_a \right) \quad (3)$$

Table 1 Simulation parameters for predicting RI sensing characteristics of the θ -shaped microfiber resonator

Coupling efficiency k	Coupling loss γ	Microfiber diameter (μm)	Cavity length L (mm)	Original RI (a.u.)
0.1	0.01	2	4	1.3320

By applying typically parameters of the θ -shaped microfiber resonator shown in Table 1 to Equations (1)-(3), we calculate the RI sensitivity of the individual θ -shaped microfiber resonator to be merely 24.58 nm/RIU. This value is much limited for most biochemical applications. To enhance the RI sensitivity, Vernier effect is expected to be generated by cascading the θ -shaped microfiber resonator with a FFPI. A typical reflection comb spectrum of the θ -shaped

microfiber resonator and transmission spectrum of the FFPI are presented in Figs. 2(a) and (b) respectively. If the free spectrum ranges (FSRs) of the θ -shaped microfiber resonator (FSR_1) and the FFPI (FSR_2) meet the rule of $FSR_1/FSR_2 = m/(m+1)$ ($m=1,2,3,\dots$), the periodicity of the resulting Vernier spectrum (FSR_r) will be:

$$FSR_r = (m+1) \times FSR_1 = m \times FSR_2 \quad (4)$$

where $FSR_1 = \lambda^2/n_{eff}L$. Equation (4) indicates that, compared with individual θ -shaped microfiber resonator, the FSR of the combined structure is magnified by $(m+1)$ times, as shown in Fig. 2(c). Then, the RI sensitivity of the combined structure can be inferred as [8]:

$$S = [FSR_2/(FSR_2 - FSR_1)] \cdot (\lambda_1/n_{eff1}) \cdot (\partial n_{eff1}/\partial n_a) = (m+1) \cdot S_1 \quad (5)$$

It is obvious that the sensitivity after cascading with a FFPI is enhanced by magnification factor $M = FSR_2/(FSR_2 - FSR_1) = m+1$, compared with the sensitivity of the individual θ -shaped microfiber resonator. Since the FSR_1 is inversely proportional to the cavity length of the resonator, the magnification factor M and the RI sensitivity could therefore be tuned by adjusting the cavity length of the resonator.

Figure 2. Vernier principle. (a) Reflection spectrum of the θ -shaped microfiber resonator; (b) Transmission spectrum of the FFPI; (c) Vernier spectrum

3. EXPERIMENT AND DISCUSSIONS

In the experiment, a θ -shaped microfiber resonator with the size of $4mm \times 2mm$ is fabricated by bending and tying a microfiber with the length of 75mm and the diameter of $2\mu m$, as illustrated in the inset of Fig. 1(b). The propagation loss of microfibers is measured as low as 1dB. Due to the thin diameter and the extremely good flexibility of the microfiber, the bending loss can be ignored. In order to keep stable, the fabricated θ -shaped microfiber resonator is placed on a Teflon-coated- silica substrate. The experimental setup for RI sensing is displayed in Fig. 1(b) where a broadband source (BBS, AS3220-BA2) and an optical spectrum analyzer (OSA, AQ6370C-20) are employed to illuminate the sensing component and measure the optical spectrum, respectively. The θ -shaped microfiber resonator functions as the sensing probe, and the FFPI with a FSR of 0.2nm is used to generate Vernier effect, as mentioned above. The surrounding RI of the θ -shaped microfiber resonator is changed by using a batch of glycerin solutions with different concentrations. The RIs of the glycerin solutions are calibrated with an Abbe refractometer.

At first, the basic RI sensing performance of the fabricated θ -shaped microfiber resonator is investigated. The surrounding RI of the microfiber resonator is changed from 1.3319 to 1.3550, with the corresponding transmission spectra being presented in Fig. 3(a). To accurately locate the peak of Vernier envelope and continuously measure the RI changing, Lorentz fitting algorithm is applied to the Vernier spectrum [8]. From Fig. 3(a), it is clearly observed that the Vernier peak red shifts as the increasing RI. The wavelength of Vernier peak as a function of surrounding RI is displayed in Fig. 3(b). The RI sensitivity is measured as 514.41nm/RIU with linearity of $R^2=0.998$.

Then the RI sensitivity tunability of the θ -shaped microfiber resonator is studied. By changing the cavity length, the Vernier spectra with different periods are obtained. Figure 3(c) shows the Vernier spectra with periods of 0.185nm, 0.194nm and 0.198nm, corresponding to the magnification factors of 12, 31 and 73. The corresponded relationships between the wavelength shifts of three microfiber resonators and surrounding RIs are shown in Fig. 3(d). It can be seen that the RI sensitivity is tuned from 311.77nm/RIU to 2460.07nm/RIU, indicating the wide tunability of the θ -shaped microfiber resonator just by adjusting the cavity length.

Figure 3. (a) The transmission spectra with different surrounding RIs; (b) the wavelength as a function of surrounding RI; (c) The Vernier spectra with periods of 0.185nm, 0.194nm and 0.198nm; (d) The corresponded relationships between the wavelength shifts of the three θ -shaped microfiber resonators and RIs.

4. CONCLUSION

In this paper, we demonstrate a compact RI probe based on θ -shaped microfiber resonator and FFPI. By cascading the θ -shaped microfiber resonator with a FFPI, Vernier effect is generated to demodulate surrounding RI with enhanced and controllable sensitivity. The experimental results show that the RI sensitivity can be widely tuned from 311.77nm/RIU to 2460.07nm/RIU. The proposed θ -shaped microfiber resonator owes intrinsic single mode fiber pigtail to directly connect with other fiber devices, thus being able to act as a compact and portable RI probe. The employed method of generating Vernier effect also offers an idea for other sensing applications to enhance and tune the sensitivities.

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