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Microfiber Fabry–Perot interferometer fabricated by taper-drawing technique and its application as a radio frequency interrogated refractive index sensor

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We propose a novel fiber Fabry–Perot interferometer (FPI) that incorporates a length of microfiber as its cavity and two fiber Bragg gratings (FBGs) as reflectors. The microfiber FPI is simply fabricated by flame-heated taper-drawing the central spot of an FBG into a section of microfiber. Ambient refractive index (RI) influences the effective index of microfiber, and thus the free spectrum range of the microfiber FPI, resulting in RI sensing. A dual-wavelength fiber laser based on the microfiber FPI is constructed, enabling radio frequency interrogation with high resolution. RI sensitivity of 911 MHz/RIU is experimentally demonstrated for microfiber FPI with equivalent diameter of 1.455 μm . Simulation results indicate that the sensitivity can be further enhanced by reducing the diameter of the microfiber. © 2012 Optical Society of America

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Micro/nanofiber has attracted increasing interest, due to its unique and promising properties, such as tight optical confinement, high fraction of evanescent fields, manageable large waveguide dispersion, field enhancement, and low optical loss through sharp bending [1]. To date, a variety of optical devices based on microfiber have been reported [2,3]. The property of high fractional evanescent fields, allowing strong evanescent wave coupling between microfiber and ambient environment, makes it very sensitive to the refractive index (RI) change of the ambient medium.

Combining fiber Bragg grating (FBG) and microfiber provides a platform for developing novel optical sensors [4]. By fabricating Bragg grating on a microfiber using a femtosecond laser, RI sensitivities of 231 nm/RIU [5] and 660 nm/RIU [6] were demonstrated. However, direct FBG writing on microfiber using a UV laser is inconvenient and usually has low reflectivity as well as low signal-to-noise ratio [7], because the photosensitive core of the fiber vanishes upon being tapered to such a small diameter, which significantly limits its application. Nano-fiber Fabry–Perot microresonators [8,9] formed by tapering the central part of two cascaded FBGs, which have high finesse and high transmittivity at its resonance wavelengths, have been reported. However, they mainly focused on the applications in cavity quantum electrodynamics.

Two wavelengths optically heterodyne of a dual-wavelength laser is a common approach for photonic generation of radio frequency (RF) signals [10–12]. The methodology is to beat two phase-coherent lasers with different wavelengths at a photodetector (PD). A beat signal can be derived from the PD with a central frequency equivalent to the frequency difference of the two wavelengths. As electrical spectrum analyzers (ESAs) have much higher frequency resolution than optical spectrum analyzers (OSAs), such a technique is more

advantageous for measuring the frequency difference of two laser beams than optical means [13]. A laser heterodyne can detect relative frequency drift of two wavelengths to the order of laser linewidth, which is commonly several kilohertz, thanks to the high frequency resolution of ESA.

In this Letter, we present a microfiber Fabry–Perot interferometer (FPI) that is composed of a length of microfiber as its cavity and two FBGs as reflectors. The microfiber FPI is simply drawn from one normal FBG by the flame-heated taper-drawing technique. Since ambient RI influences the effective index of microfiber, the free spectrum range (FSR) of the microfiber FPI, which approximately equals the spacing of two adjacent reflection peaks of microfiber FPI, is susceptible to the ambient RI. A dual-wavelength fiber laser that oscillates at two adjacent reflection peaks of microfiber FPI is constructed. Its output is detected by a PD, which generates a beat signal with central frequency equivalent to the spacing of two lasing wavelengths. Consequently, high sensitive ambient RI sensing could be realized by measuring the beat frequency.

Figure 1 illustrates the configuration of a microfiber FPI fabrication platform. An FBG (denoted as FBG0) is installed on two translation stages through two fiber

Fig. 1. (Color online) Schematic diagram of the microfiber FPI fabrication process.

holders. Right after a hydrogen flame is placed beneath the center of FBG0, we control the translation stages to move toward the opposite directions, so that the partial fiber is stretched into a small diameter. When the microfiber reaches desirable length and diameter, we stop the translation stages and remove the flame quickly. In this way, the original FBG0 is split into two FBGs (FBG1 and FBG2), and a length of microfiber between them is obtained. As a result, an FPI incorporating microfiber as cavity and FBG1 and FBG2 as reflectors can be derived. Its structure is depicted in the inset of Fig. 1. The process is similar to regular taper-draw technique [1,14] except that the microfiber is drawn at the center of one FBG, not on a single-mode fiber.

The transfer function of the microfiber FPI is deduced as

$$\begin{bmatrix} a(z_1) \\ b(z_1) \end{bmatrix} = \begin{bmatrix} e^{j\beta L} & 0 \\ 0 & e^{-j\beta L} \end{bmatrix} F_2 \begin{bmatrix} t & 0 \\ 0 & 1/t \end{bmatrix} \times \begin{bmatrix} e^{-j(\beta-\beta')l} & 0 \\ 0 & e^{j(\beta-\beta')l} \end{bmatrix} F_1 \begin{bmatrix} a(z_0) \\ b(z_0) \end{bmatrix}, \quad (1)$$

where $a(z_0)$ and $b(z_0)$ are the forward and backward light at one end of microfiber FPI; $a(z_1)$ and $b(z_1)$ are the forward and backward light at the other end; β' and β are propagation constants of microfiber and the optic fiber used to fabricate the original FBG0; t and l are the transmittance and length of microfiber, respectively; L is the total length of the microfiber FPI; and F_1 and F_2 are transfer matrices of FBG1 and FBG2, which are given in [15]. The reflection of microfiber FPI, expressed as $R = |b(z_0)/a(z_0)|^2$, can be seen as interference fringes induced by FPI overlap on the reflection profiles of two FBGs. Figure 2 gives the measured reflection spectrum of a microfiber FPI consisting of two 2 mm-long tapers and an 8 mm-long microfiber, which is fabricated by taper-drawing at the center of an FBG0 with a length of 15 mm, central wavelength of 1540.6 nm, and 3 dB bandwidth of 0.15 nm. Interferences fringes with extinction ratio ~ 10 dB and an envelope similar to FBG reflection spectrum can be observed. By comparing the measured spectrum to the simulation result, we derive that the finesse of microfiber FPI is 3 and transmittivity at resonance wavelength is larger than 48.4%. Precisely speaking, the microfiber is a biconical fiber

Fig. 2. (Color online) Reflection spectra of microfiber FPI and uniform FBG3.

taper [16] with a uniform waist of about 6 mm length and about $1.3 \mu\text{m}$ diameter.

We introduce the effective index of microfiber $n_{\text{eff}} = \lambda_0 \beta' / (2\pi)$, where λ_0 is the operating wavelength, and effective cavity length of microfiber FPI l_{eff} , which is calculated by [17], to analyze the RI response of microfiber FPI. The fringes period, i.e., FSR of microfiber FPI, can be described as

$$\text{FSR} = \frac{c}{2n_{\text{core}}(l_{\text{eff}} - l) + 2n_{\text{eff}}l}, \quad (2)$$

where n_{core} is the RI of fiber core. As n_{eff} depends on ambient RI [14], relation between ambient RI and FSR as well as the beat frequency of microfiber is achieved. Ambient RI variation is interpreted as a change of wavelength spacing between two adjacent reflection dips of microfiber FPI (i.e., FSR). It can be inferred that the spacing between two adjacent reflection peaks is approximately equal to FSR and should have identical response to ambient RI due to the periodicity of interference fringes.

In the RI sensing experiment, a fiber laser employing the microfiber FPI and a uniform FBG (denote as FBG3; reflection spectrum shown in Fig. 2) as the resonant cavity surfaces is built for RF interrogation, as illustrated in Figure 3. The gain medium is a piece of 3 m long erbium doped fiber (EDF, Verrillon EDF-1-125) pumped by a 980 nm laser diode via a wavelength division multiplexer (WDM). A 1 m long EDF is incorporated as a saturable absorber (SA) to ensure single-longitudinal-mode operation of the fiber laser. The central wavelength of FBG3 can be strain-tuned from 1540.6 nm to 1543 nm by translation stages, with 3 dB reflection bandwidth 0.16 nm. The microfiber FPI is immersed in sucrose solution and confined in a plastic tube, with the FSR of around 40 pm. The output laser power is amplified by an erbium doped fiber amplifier to -5 dBm to facilitate the detection. A 3 dB coupler separates the optical power into two parts for simultaneous measurement of optical spectrum by OSA (Yokogawa AQ6370C) and frequency spectrum by ESA (Agilent E4447A) through a PD (New Focus 1014).

As the reflection bands of FBG3 cover more than two reflection peaks of microfiber FPI, the laser will have dual-wavelength or multiwavelength emission. In fact, multiwavelength emission is not observed in the experiment because of gain competition in EDF. On the contrary, stable dual-wavelength lasing can be easily achieved when the Bragg wavelength of FBG3 is tuned to the center of the reflection band of microfiber FPI. A typical

Fig. 3. (Color online) Experimental setup for RF domain interrogation of the RI sensor.

Fig. 4. (Color online) (a) Optical spectrum and (b) beat spectrum of the dual-wavelength fiber laser when the ambient RI is 1.3915.

Fig. 5. (Color online) Dependence of FSR of microfiber FPI, i.e., beat frequency of the dual-wavelength fiber laser, on ambient RI. Plotted in the figure include experimental results (red cross) and simulation results for different microfiber diameters (curves). In the simulation, the l_{eff} is set to be 20.2 mm and the lengths of FBG1 and FBG2 are 5.67 mm. The values are chosen in accordance with the physical dimension of microfiber FPI.

dual-wavelength laser spectrum is given in Figure 4(a), with two peaks at 1541.032 nm and 1541.072 nm, respectively, the wavelength spacing of which is equal to the FSR of microfiber FPI. Figure 4(b) is the corresponding beat spectrum with a central frequency of 5.240 GHz.

To change the ambient RI of microfiber FPI, a batch of sucrose solution with different concentration is tested in the experiment. After each test, we drain out the used sucrose solution, thoroughly rinse and clean the plastic tube in which the microfiber FPI is confined, and then inject new sucrose solution. The corresponding RI of the solution is detected by an Abbe refractometer as reference.

Beat frequencies at different sucrose concentration are measured, as shown in Fig. 5. As ambient RI increases from 1.334 to 1.400, and the beat frequency decreases from 5.29 GHz to 5.23 GHz. The RI sensitivity is 911 MHz/RIU (RI units). Simulation results for the identical FPI configuration for microfiber with uniform diameters ranging from 1 μm to 3 μm are also presented. It can be referred from Fig. 5 that higher RI sensitivity can be achieved by reducing the diameter of microfiber. For instance, with microfiber diameter of 1 μm , the RI

sensitivity is 1.33 GHz/RIU. Experimental results are in good agreement with simulation for microfiber diameter of 1.455 μm , which can be considered as the equivalent uniform diameter for the taper-drawn microfiber (biconical fiber taper) with waist diameter of 1.3 μm .

In conclusion, we propose a novel microfiber FPI incorporated by a length of microfiber as a cavity and two FBGs as reflectors. The microfiber FPI is simply fabricated by taper-drawing an FBG at its center. Its application as a high sensitivity RI sensor is demonstrated based on a dual-wavelength fiber laser. RI sensing with sensitivity of 911 MHz/RIU is realized by beating two output wavelengths that oscillate at two adjacent reflection peaks of the microfiber FPI. Moreover, RI sensitivity of up to 1.33 GHz is theoretically demonstrated by reducing the microfiber diameter to 1 μm . Because of its simplicity for fabrication, low cost, and capability for multiplexing, such microfiber FPI has great application potential in optical and bio sensing areas.

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References

1. L. Tong, R. R. Gattass, J. B. Ashcom, S. He, J. Lou, M. Shen, I. Maxwell, and E. Mazur, *Nature* **426**, 816 (2003).
2. P. Polynkin, A. Polynkin, N. Peyghambarian, and M. Mansuripur, *Opt. Lett.* **30**, 1273 (2005).
3. J. Wo, G. Wang, Y. Cui, Q. Sun, R. Liang, P. P. Shum, and D. Liu, *Opt. Lett.* **37**, 67 (2012).
4. R. Liang, Q. Sun, J. Wo, and D. Liu, *Opt. Commun.* **285**, 1128 (2012).
5. X. Fang, C. Liao, and D. Wang, *Opt. Lett.* **35**, 1007 (2010).
6. Y. Liu, C. Meng, A. P. Zhang, Y. Xiao, H. Yu, and L. Tong, *Opt. Lett.* **36**, 3115 (2011).
7. Y. Ran, Y. N. Tan, L. P. Sun, S. Gao, J. Li, L. Jin, and B. O. Guan, *Opt. Express* **19**, 18577 (2011).
8. C. Wuttke, M. Becker, S. Brückner, M. Rothhardt, and A. Rauschenbeutel, *Opt. Lett.* **37**, 1949 (2012).
9. K. Nayak, F. Le Kien, Y. Kawai, K. Hakuta, K. Nakajima, H. Miyazaki, and Y. Sugimoto, *Opt. Express* **19**, 14040 (2011).
10. Q. Sun, J. Wang, J. Wo, X. Li, and D. Liu, *Microwave Opt. Technol. Lett.* **53**, 2478 (2011).
11. S. Pan and J. Yao, *Opt. Express* **17**, 12167 (2009).
12. X. Chen, Z. Deng, and J. Yao, *IEEE Trans. Microwave Theory Tech.* **54**, 804 (2006).
13. J. Huang, X. Lan, T. Wei, Q. Han, Z. Gao, Z. Zhou, and H. Xiao, *Opt. Lett.* **37**, 494 (2012).
14. L. Tong and M. Sumetsky, *Subwavelength and Nanometer Diameter Optical Fibers* (Springer Verlag, 2010).
15. T. Erdogan, *J. Lightwave Technol.* **15**, 1277 (1997).
16. M. Sumetsky, Y. Dulashko, J. Fini, A. Hale, and J. Nicholson, *Opt. Lett.* **31**, 2393 (2006).
17. W. Ren, P. Tao, Z. Tan, Y. Liu, and S. Jian, *Chin. Opt. Lett.* **7**, 775 (2009).