

A miniature reflective micro-force sensor based on a microfiber coupler

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Abstract: A compact highly sensitive microfiber coupler based reflective micro-force sensor is presented. The device is fabricated by fusing two twisted optical fibers and then connecting two of the pigtails to form a Sagnac loop. The sensor has a high force sensitivity of ~ 3754 nm/N which is three orders of magnitude larger than traditional optical fiber force sensors, and a low detection limit of ~ 1.6 μ N. The good repeatability is also shown in this paper.

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OCIS codes: (230.1150) All-optical devices; (060.2340) Fiber optics components; (060.1810) Buffers, couplers, routers, switches, and multiplexers; (060.2370) Fiber optics sensors.

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1. Introduction

Force sensing is of great importance in many applications such as structure inspection of aircraft, civil infrastructure and earthquake monitoring. Recently fiber based force sensors have been developed rapidly because of their insensitivity to electromagnetic fields, light weight, minimal intrusiveness, ease of termination and coupling. Different types of force sensors based on highly birefringent (Hi-Bi) fibers, Mach-Zehnder (M-Z) interferometers, fiber Bragg gratings (FBGs), etc. have been demonstrated. The Hi-Bi fiber force sensor [1] needs to use expensive fiber. The M-Z interferometer-based force sensor [2] has a complicated sensing structure and is hard to be fabricated. Force sensor using FBG [3–6] mainly operates by monitoring the shift of Bragg wavelength which is caused by applied force. In order to realize the temperature and force discrimination, the FBG based sensor usually has a complicated structure. In addition, FBG is very fragile and the sensitivity of a typical FBG based force sensor is only ~ 1 nm/N. However, in many practical applications, particularly micro-force measurements, the force sensor should be low-cost, compact, simply structured, easily fabricated as well as highly sensitive and have a low detection limit.

Since a seminal paper published in 2003 [7], microfiber has received a lot of attention because of its low loss, large evanescent field, strong confinement, configurability and robustness. Compact devices based on microfiber such as loop resonators [8], knot resonators [9], and coil resonators [10] have been investigated. Recently, a microfiber FBG based force sensor was demonstrated by Luo *et al.* [11] with a sensitivity of ~ 3146 nm/N. But the fabrication method using focused ion beam (FIB) leads to a high cost and low production. Moreover, the fragile structure and high loss (~ 13 dB) limit its application. In 2009, a broadband single mode microfiber coupler (MFC) was demonstrated by Jung *et al.* [12]. MFCs have many applications in optical communication [13], wavelength measurement [14] and sensing [15] due to their good performance and low cost. In reference [15], Ding *et al.* demonstrated a compact thermometer based on a MFC tip for high temperature sensing. The device had a large loss (~ 20 dB) mainly because of the poor reflection at the tip end face. Further processing is needed to enhance the reflection of MFC tip [16]. In this paper, a low loss miniature highly sensitive force sensor based on a MFC is presented. We constructed a Sagnac loop to reflect the light and gained a low loss of ~ 1 dB which was mainly due to the insertion loss caused by the bare fiber adaptors. The fabricated device has the advantages of low cost (made by commercial single-mode fibers), simple structure (fused optical fiber coupler), compact size (microfiber based device), easily fabricating (flame-brushing method) as well as high sensitivity (~ 3754 nm/N) and low detection limit (< 1.6 μ N).

2. Theoretical analysis

Figure 1 shows the schematic of a MFC. MFCs are manufactured by laterally fusing and tapering two twisted optical fibers. A MFC comprises two conical transition regions, a central uniform waist region and four input/output ports: light injected into ports P_1 or P_2 exits from ports P_3 and P_4 .

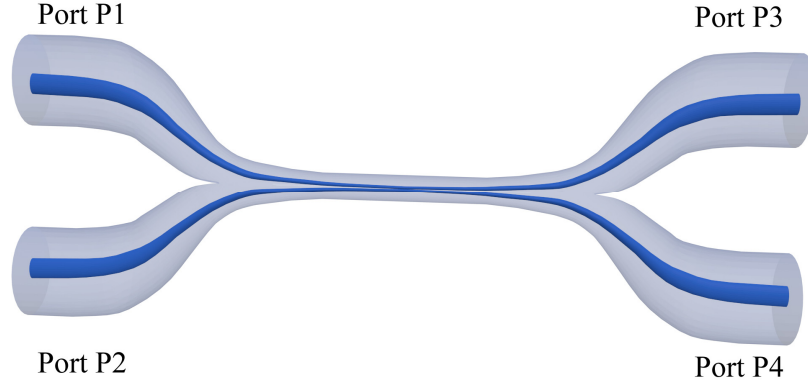


Fig. 1. Schematic of a MFC.

The MFC can be assumed as a weakly fused coupler, approximated by two touching cylindrical waveguides. The coupling coefficients for the x and y polarizations are given by [17]:

$$C_x = \frac{2^{3/2} (n_1^2 - n_0^2)^{1/2} U_\infty^2 (2n_1^2 V + 1)}{n_1^3 a (\sqrt{\pi}) V^{7/2}} \quad (1)$$

$$C_y = \frac{2^{3/2} (n_1^2 - n_0^2)^{1/2} U_\infty^2 (2n_1^2 V - 1)}{n_1^3 a (\sqrt{\pi}) V^{7/2}} \quad (2)$$

where n_1 and n_0 refer to the refractive indices of silica and air, a denotes the diameter of one of the microfibers, $U_\infty = 2.405$ and $V = [(2\pi a)/\lambda](n_1^2 - n_0^2)^{1/2}$.

Figure 2 demonstrates the structure of our device. We connect ports P₃ and P₄ together to form a Sagnac loop. If light entering the input port P₁ is unpolarized, the normalized power at the output port P₂ can be described by:

$$P_2 = \frac{1}{2} \left\{ 1 + \cos[2(\overline{C}_x + \overline{C}_y)L_{\text{coupler}}] \cos[2(\overline{C}_x - \overline{C}_y)L_{\text{coupler}}] \right\} \quad (3)$$

where L_{coupler} is the coupling length of the MFC, \overline{C}_x and \overline{C}_y are the values of Eqs. (1) and (2) averaged over the whole coupling region. Because of the large modal size and the relatively small overlap, the contribution of the transition regions is negligible.

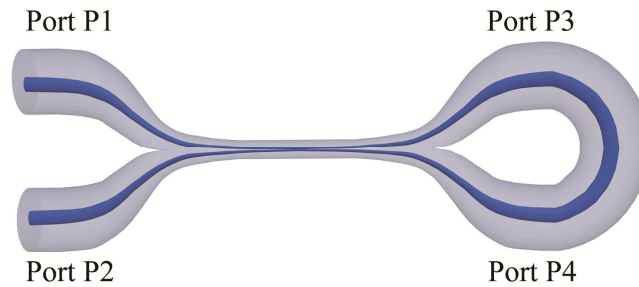


Fig. 2. Structure of the miniature MFC Sagnac loop.

Equations (1)–(3) exhibit that the output power depends on the wavelength λ , refractive index n_1 , coupling length L_{coupler} , and coupler radial size $2a$. A longitudinal mechanical force f

applied to the device will induce both refractive index n_1 and coupling length L_{coupler} to change, which can be predicted by following formulas [11, 18, 19]:

$$\frac{\Delta L_{\text{coupler}}}{L_{\text{coupler}}} = \varepsilon_{\text{coupler}} = \frac{f}{EA_{\text{coupler}}} \quad (4)$$

$$\frac{\Delta n_1}{n_1} = -\frac{f}{EA_{\text{coupler}}} \times P \quad (5)$$

$$P = \frac{n_1^2}{2} [p_{12} - \nu(p_{11} + p_{12})] \quad (6)$$

where E is the Young's modulus of the fiber material, $\varepsilon_{\text{coupler}}$ is the applied strain on coupling region, and A_{coupler} is the area of coupling region cross section which can be calculated by $A_{\text{coupler}} = 2\pi(a/2)^2$, ν is the Poisson ratio, p_{11} and p_{12} are the components of Pockel's strain-optical tensor of the fiber material, respectively. P is the effective photo-elastic coefficient.

The force dependence of the device output spectrum around 1550 nm can be evaluated by assuming first 1×10^{-4} N and then 2×10^{-4} N longitudinal mechanical forces are applied on the device, respectively. We assume $L_{\text{coupler}} = 1$ cm, $a = 1.6 \mu\text{m}$, $p_{11} = 0.113$, $p_{12} = 0.252$, $\nu = 0.17$, and $E = 73$ GPa in our calculation, respectively. The refractive index n_1 and coupling length L_{coupler} will then vary with the force and result in the change of the output spectrum. Figure 3 shows the output power variation under three different mechanical forces. The peak wavelength has a blueshift of ~ 734 pm when the force increases from 0 N to 2×10^{-4} N, with an average sensitivity of ~ 3670 nm/N.

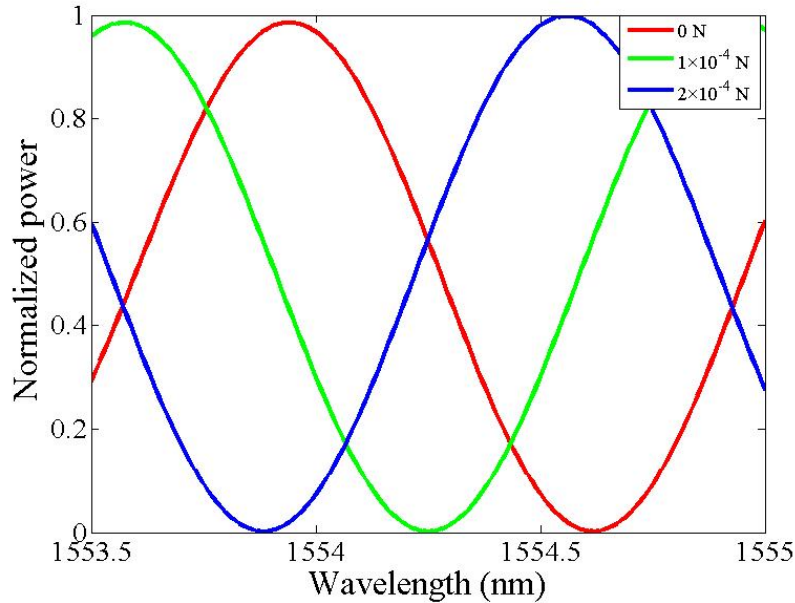


Fig. 3. The calculated output power from port P_2 under three different mechanical forces.

We then calculate the dependence of force sensitivity S on the microfiber diameter a around 1550 nm wavelength. As revealed in Fig. 4, S increases quickly with the decreasing diameter.

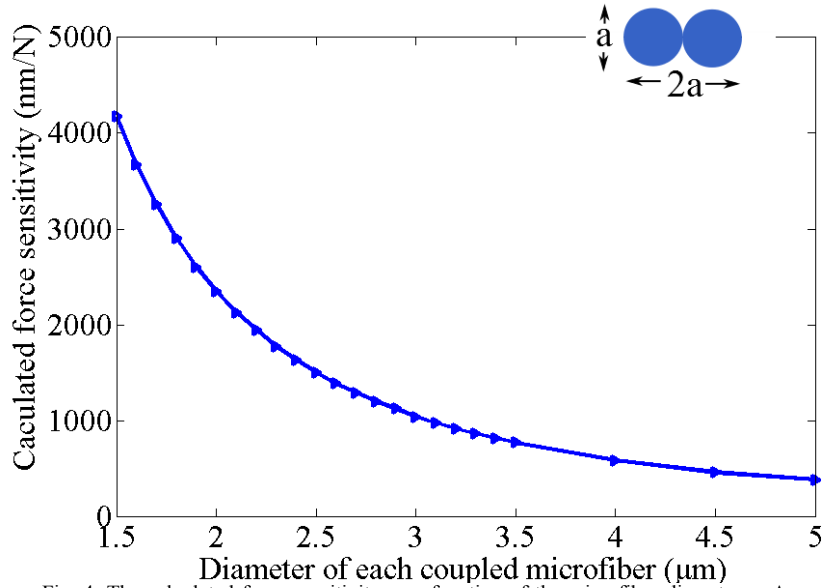


Fig. 4. The calculated force sensitivity as a function of the microfiber diameter a . A smaller diameter will cause a higher sensitivity. Inset: cross section of the MFC coupling region in the “weakly fusing” approximation.

3. Experiment and discussion

First, a MFC was fabricated from two standard telecom optical fibers (SMF-28, Corning, NY, USA) using the flame brushing method [20]. Figures 5(a) and 5(b) illustrate the microscope images of the MFC: the diameter of each coupled microfiber was $\sim 1.6 \mu\text{m}$, the coupling region length was $\sim 1 \text{ cm}$. Then, ports P_3 and P_4 were connected together using a commercial fusion splicer to form a Sagnac interferometer.

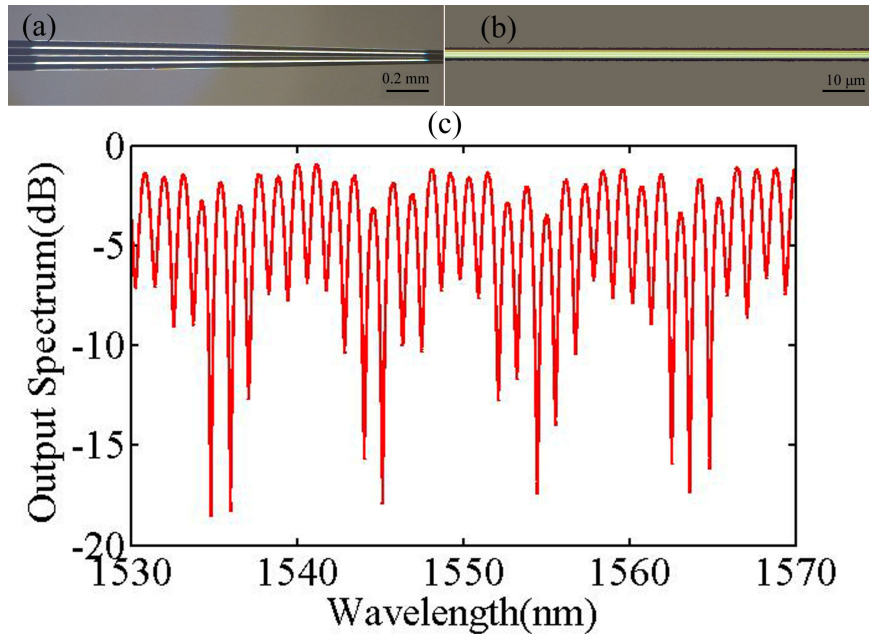


Fig. 5. Microscope images of (a) the transition region and (b) coupling region of the MFC, the diameter of each coupled microfiber is $\sim 1.6 \mu\text{m}$; (c) Output spectrum at port P_2 .

The spectral characterization of our device was carried out by connecting a supercontinuum (SC) source (NKT Photonics), with emission over the wavelength range 1200-1700 nm, to port P₁ and an optical spectrum analyzer (OSA) (AQ6317C, Yokogawa, Japan) to port P₂. The output spectrum at room temperature is presented in Fig. 5(c). It shows a multi-peak pattern due to lower-order symmetric and anti-symmetric supermodes interference in the coupling region. We can see a slow modulation of the spectral envelope which can be explained by the different coupling coefficients for *x* and *y* polarizations [21, 22].

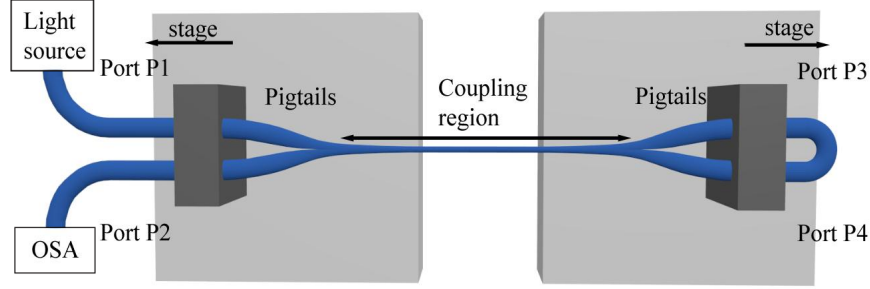


Fig. 6. Schematic of the measurement setup.

The measurement setup is shown in Fig. 6. The device was held on two stretch stages. Port P₁ was connected to the broadband light source (NKT, SuperK Versa) and port P₂ was connected to the OSA (Ando AQ6317C). Light from the source goes through the sample and then into the OSA. As we controlled the stages to move away from each other, a longitudinal force would be applied on the coupler and thus influence the refractive index and coupling length. As the force changed the lengths of both the coupling region and pigtailed:

$$L_{\text{coupler}} + L_{\text{pigtail}} = L_{\text{fiber}} \quad (7)$$

$$\Delta L_{\text{coupler}} + \Delta L_{\text{pigtail}} = L_{\text{stretch}} \quad (8)$$

where L_{coupler} and L_{pigtail} refer to the length of coupler region and fiber pigtailed between the two stretch stages. L_{fiber} is the total length of the above two parts, i.e. the distance between the two stretch stages. In our experiment $L_{\text{fiber}} = 1.3$ cm. $\Delta L_{\text{coupler}}$ and $\Delta L_{\text{pigtail}}$ are the length changes of the coupling and pigtail regions, respectively. The forces applied to the coupling region and to the pigtail region are equal [18]:

$$\varepsilon_{\text{coupler}} EA_{\text{coupler}} = \varepsilon_{\text{pigtail}} EA_{\text{pigtail}} \quad (9)$$

where A_{coupler} and A_{pigtail} are the cross sectional areas of coupling and pigtail regions, respectively. $\varepsilon_{\text{coupler}}$ and $\varepsilon_{\text{pigtail}}$ refer to the applied strain on the relevant region. Then the relationship between the stretched distance and the force can be predicted by using Eqs. (4) and (7)–(9). In our experiment, each stage moved 1 μm per-step, $L_{\text{stretch}} = 2 \mu\text{m}$, thus the applied force f increased 5.86×10^{-5} N per-step.

Figure 7 reports the output spectrum of the device under different forces. When the applied force rises from 4.10×10^{-4} N to 5.27×10^{-4} N, the peak wavelength blueshifts from 1552.96 nm to 1552.53 nm.

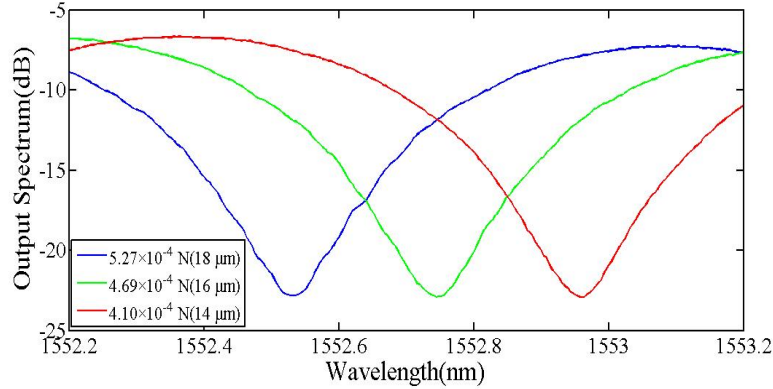


Fig. 7. Output spectrum of the device around the peak wavelength 1553 nm under different forces.

The sensitivity is defined as the wavelength shift associated to the force change. Figure 8 illustrates the peak wavelength shift against the applied force. In this experiment, the applied force varied from 0 N to 7.03×10^{-4} N (i.e. the stretched length rose from 0 μm to 24 μm).

The force sensitivity S is ~ 3754 nm/N, which is three orders of magnitude larger than that of traditional optical fiber force sensors. The explanation for the difference between the theoretical calculation and experimental data could be the imperfect weakly fused coupler simplification in theory and the refractive index error. The sensor detection limit can be defined as $\delta\lambda_0/S$, where $\delta\lambda_0$ is the smallest measurable wavelength shift. Generally, $\delta\lambda_0$ is limited by instrument resolution and is assumed as 1/50 of the full width at half maximum (FWHM) of the monitored resonance. The sensor detection limit was estimated to be ~ 1.6 μN for a FWHM of ~ 0.3 nm. Lower detection limit ($\sim \text{nN}$) possibly can be achieved with better instruments and optimized fabrication.

The force measurement repeatability was also evaluated by recording spectra with increasing and decreasing forces. As we can see from Fig. 8, data from the two curves coincide with each other, showing that the device has a good repeatability.

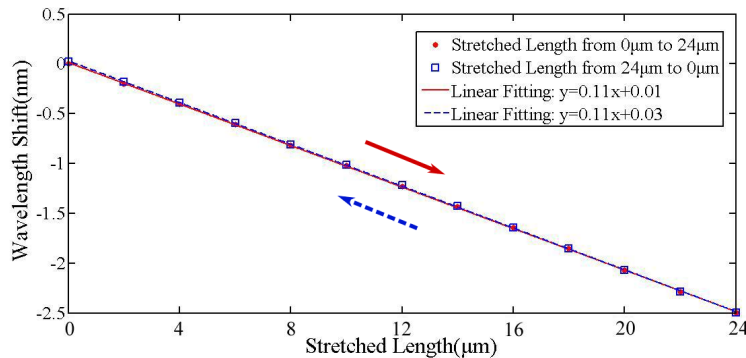


Fig. 8. Wavelength shift dependence on the stretched length. The red and blue curves refer to increasing and decreasing forces, respectively.

4. Conclusion

In this paper, we demonstrate a compact highly-sensitive microfiber coupler based reflective micro-force sensor. The device is fabricated by fusing two twisted optical fibers (SMF-28) and then connecting two of the pigtails to form a Sagnac loop. The sensor has a high force sensitivity of ~ 3754 nm/N with a good repeatability around the wavelength of 1553 nm, about three orders of magnitude larger than that of traditional optical fiber force sensors. The device

has a large potential in many applications such as micro-force detection, structure inspection of aircraft and earthquake monitoring.

Acknowledgments

This work is supported by National 973 program under contract No. 2012CB921803 and 2011CBA00205, NSFC program No. 11074117 and National Science Fund for Excellent Young Scientists Fund (61322503) and National Science Fund for Distinguished Young Scholars (61225026). The authors also acknowledge the support from PAPD and the Fundamental Research Funds for the Central Universities. The authors thank Wei Guo, Bi-cai Zheng, and Guang-hao Shao for their kindly help.