

# Rough side-polished fiber with surface scratches

## for sensing applications

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**Abstract:** We demonstrated a fast mechanical wheel lapping technique to fabricate a convenient and low cost side-polished fiber (SPF) with a rough, rather than smooth, polished surface. Such a bare SPF can be directly used to develop a promising sensing device, because Mach-Zehnder interference pattern with high fringe contrast above 10 dB in transmission spectrum was achieved due to the macro scratches on the rough polished surface. Fabrication parameters, e.g. thickness of remained fiber, polished length and the roughness of abrasive paper were optimized. The sensor exhibited strain and temperature sensitivities up to  $-2.00 \text{ pm}/\mu\epsilon$  and  $29.37 \text{ pm}/^\circ\text{C}$ , and can be used to realize simultaneous strain and temperature measurement.

**Index Terms:** Optical fiber sensors, side polished fiber, surface scratch. Mach-Zehnder Interference.

### 1. Introduction

Side polished fiber (SPF) have been widely used in a variety of applications including direction couplers, attenuators, polarizers, switches, resonators, filters and evanescent fiber sensors, owing to the well-known evanescent field on the polished fiber surface [1-4]. Most of these components share a common fabrication process that a single mode fiber is glued by epoxy into a cutting curved V-shaped groove with its cladding polished away over a limited interaction length of several millimeters [5]. According to the fiber diameter and the remained cladding thickness, different size of the V-shaped grooves have to be made precisely in advance by complicate techniques to achieve a desired SPF, which results in a low efficiency and a high cost. Alternatively, wheel polishing technique is more efficient by using a rolling wheel dressed with abrasive to polish fiber fixed on the flat surface. Since the V-shaped groove is not required, SPF with long interaction region can be realized flexibly by wheel polishing technique [6]. The distance from the polished surface to the fiber core, i.e. so-called remained cladding thickness,  $d$ , can be measured by liquid-drop method [7-8]. Usually, a standard SPF fabrication begins with a rough lapping process by coarse abrasive and then is followed by a fine polishing process to remove the surface scratches. However, complicated post processing always takes a long time to create a high quality SPF with smooth surface, which is a bottleneck to the SPF's applications.

In this paper, we demonstrated a fast mechanical wheel lapping technique to fabricate a convenient and low cost SPF with a rough, rather than smooth, polished surface. Such a bare SPF exhibits clear interference fringes in transmission spectrum and can be used to develop promising fiber sensors, e.g., strain and temperature sensor. The scratches on the rough polished surface are the secret.

## 2. Experimental Details

As shown in Fig.1 (a), a wheel polishing setup (WanRun Ltd., WuXi, China) was employed to fabricate a SPF [9]. A cylinder grinding wheel was fastened on a precise 3-dimension translation platform that can be moved along the X, Y and Z directions via computer control. Here, the wheel axis and the fiber axis were defined as the Z and Y direction, respectively. Firstly, a standard SMF (Corning SMF-28) with a core/cladding diameter of 8.2/125  $\mu\text{m}$  was fixed by a pair of fiber holders. A 20g weight was hung to provide a constant tension to the polished fiber. The fiber coating was stripped in advance over a section of polished length and then cleaned by alcohol. Secondly, the coarse abrasive paper was winded and fastened around the wheel with paroline dropped onto the abrasive paper as lubrication. Thirdly, the wheel was drive down along the Z directions. Here, the rolling speed of the wheel and moving distance along the Y direction were preset in the computer. Then, the unjacketed fiber was gradually polished by the rolling wheel moving forth and back along the Y direction. During the polishing process, the side view of the SPF was monitored along the X direction by use of a microscope. Fig. 1 (b) illustrates the side view of an achieved SPF. The remained fiber thickness, ' $D$ ', of the SPF sample was measured along the whole polished region, as shown in Fig. 1 (c). It can be found that the 8.5mm-length SPF sample consists of a flat region with a length of about 4.0 mm and two tapered transition regions with a length of about 2 to 2.5 mm.

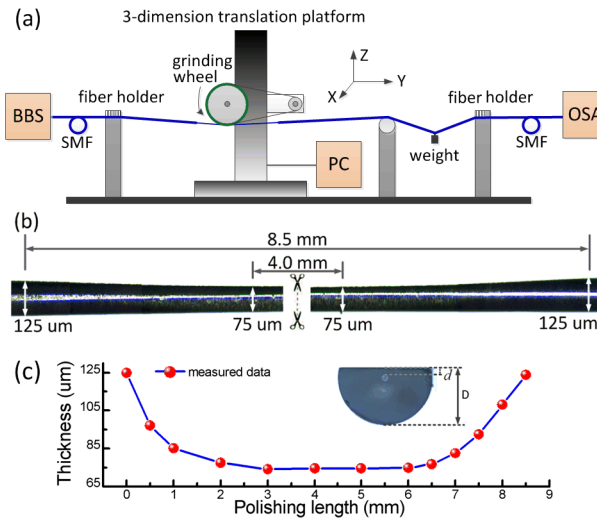


Fig. 1. (a) Schematic of the wheel polishing setup; (b) Microscope image of the achieved SPF; (c) Measured remained thickness of the SPF along the whole polished region. The inset shows the cross section of the SPF where ' $d$ ' and ' $D$ ' is the remained cladding and fiber thickness respectively.

A broadband light source (BBS) light source with the range of 1250nm to 1650nm and an optical spectrum analyzer (OSA, YOKOGAWA AQ6370C) were employed to measure the transmission profile of SPF during the polishing process [10]. Coarse abrasive papers (800-mesh, 1500-mesh, 3000-mesh, Warriors 991A, STABCKE, Germany) were chose to fabricated SPF samples with different surface roughness. The particle size of 800-mesh, 1500-mesh and 3000-mesh abrasive was 19 $\mu\text{m}$ , 10 $\mu\text{m}$  and 5 $\mu\text{m}$  respectively. After each lapping step, the polished surface was gently cleaned by an air-laid paper with alcohol to wipe off the residual silica dust and paroline. Noting that the position of polished surface cannot be changed to reduce the measurement error of ' $D$ ', and the SPF need to be always straighten naturally to avoid small bend perturbation.

## 3. Parameter Optimization

To investigate the influence of the remained fiber thickness, the 800-mesh abrasive paper was employed to fabricate a rough SPF with polished length of 30 mm. Fig. 2 and the inset show the evolution of transmission profile and power loss during the whole lapping process. At early stage of the process, when remained fiber thickness ' $D$ ' stay above 75  $\mu\text{m}$  (i.e.  $d > 8 \mu\text{m}$ ), light was fully guided in the fiber core and the power loss can be ignored. As the polished depth increased continually, the power loss gradually increased first and then rose sharply with ' $D$ ' reduced to less than 72  $\mu\text{m}$  (i.e.  $d < 5 \mu\text{m}$ ). While the SPF was lapped to near the core region, usually ' $D$ ' was below 69  $\mu\text{m}$  (i.e.  $d < 2 \mu\text{m}$ ), interference pattern was observed in the transmission spectrum and the fringe contrast increased with the continual reduction of ' $d$ '. It could be considered as the interference between the core mode and the cladding modes induced by the surface scratches which will be analyzed in the following content. However, when the SPF was lapped into the fiber core, usually when ' $D$ ' was less than 66  $\mu\text{m}$ , (i.e.  $d < -1 \mu\text{m}$ ), the fringe contrast gradually decreased due to the cutoff some cladding modes [11]. To achieve high contrast interference patterns, ' $D$ ' was always controlled between 66 to 68  $\mu\text{m}$  in fabrication.

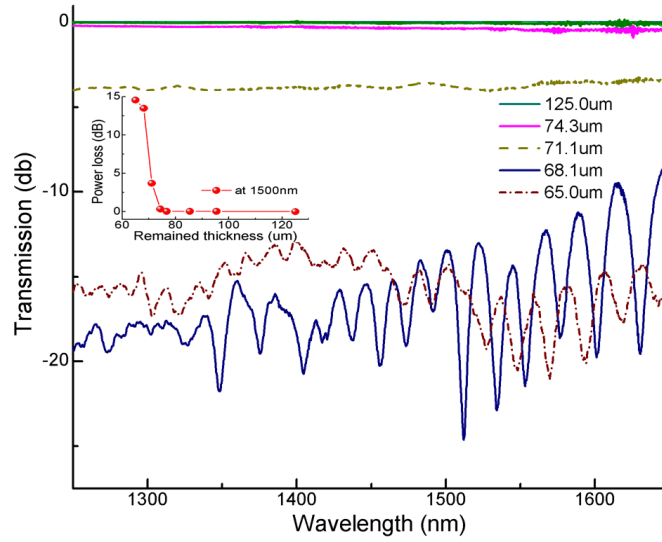


Fig. 2. Transmission spectrum evolution of 30.0 mm-length SPF fabricated by 800-mesh abrasive, when remained fiber thickness 'D' reduced from 125.0um to 65.0um.

To investigate the influence of surface roughness on the transmission spectrum, three samples, i.e. SPF1, SPF2, and SPF3, with the same polished length of 30mm were fabricated by 800, 1500, and 3000-mesh coarse abrasive papers respectively. The lapping process was stopped as soon as a relative high contrast fringe pattern was observed in the spectrum. Top views of the polished surface from three SPFs were observed by 500X SEM (JSM-5910LV, Scanning Electron Microscope, JEOL, Japan). Fig. 3 (a) shows the polished surface of SPF1 fabricated by the 800-mesh abrasive paper, which is the roughest one with wide and deep macro scratches parallel to each other along the fiber axis. The polished surface of SPF2 shown in Fig. 3 (b) is similar to SPF1 but the size of scratches is smaller. In contrast, SPF3 shown in Fig. 3 (c) is the smoothest one with a relatively uniform surface without obvious macro scratches. Transmission profiles of SPF1 and SPF2 are shown in Fig. 3 (d) and 3 (e). Sinusoid spectral profile with high fringe contrast above 10dB at maximum in the range of 1450 to 1650nm was observed. Whereas for smoother SPF3 by fine 3000-mesh abrasive, the irregular interference pattern with higher insertion loss above 30dB was observed in Fig. 3 (f). FFT analysis of transmission spectrum was conducted. As shown in Fig. 3 (i), it can be seen that multiple peaks existing in the FFT of SPF3, indicating that several cladding modes take part in the interference with the core mode. Whereas for FFT of SPF1 and SPF2 shown in Fig. 3 (g) and (h), obviously only one main peak exist in FFT diagram, indicating that mainly one cladding mode engaged in the interference with the core mode, which agree with the sinusoid spectrum show in Fig. (d) and (e).

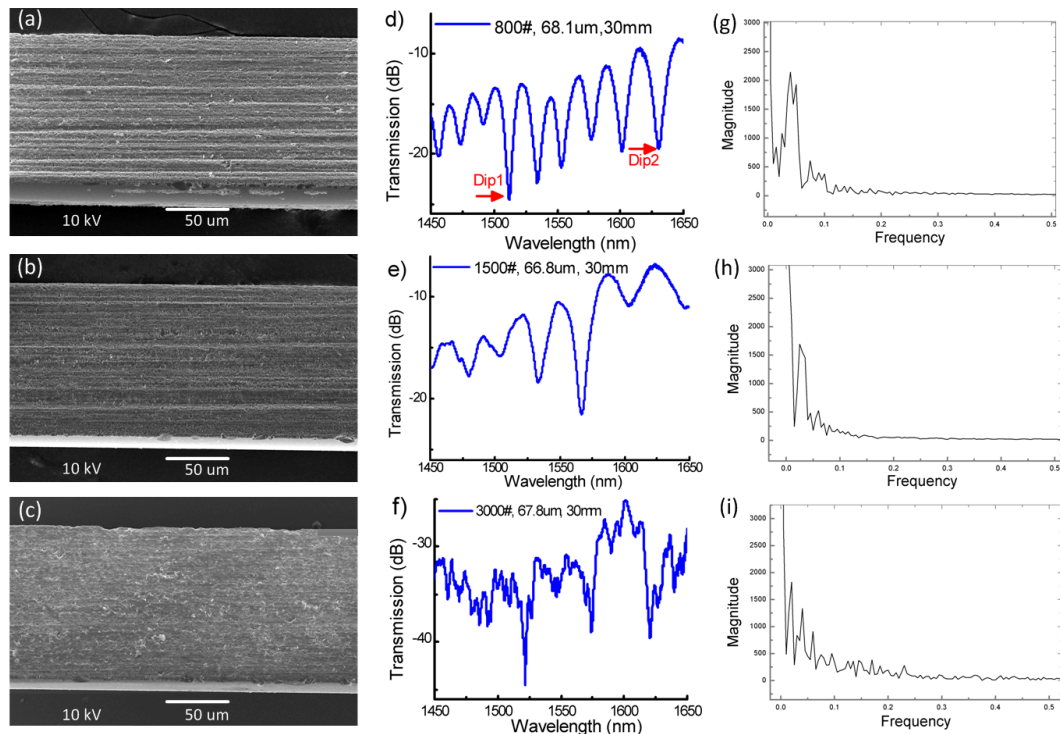


Fig. 3. Three samples SPF1, SPF2, and SPF3 were fabricated by 800, 1500, and 3000-mesh abrasive paper respectively. (a), (b) and (c) Top views of the polished surface of SPFs; (d), (e), and (f) their corresponding transmission spectra; and (g), (h), (i) FFT analysis for three SPFs.

Surface scratches observed here were naturally formed by the movement of the mechanical rolling wheel. Instead of ideal parallel line, scratches observed by 5000X SEM were discontinuous and malposed, as shown in the inset of Fig. 4. To simplify the analysis, an approximate Mach-Zehnder interferometer (MZI) model was proposed. In Fig. 4, parts of light transmitted in the core was excited into the cladding by the first scratch and then re-coupled back into the core region by the next one, resulting in the interference between the core and cladding modes. This phenomenon is similar to the interference of two cascaded long period fiber gratings [12-13]. For SPF fabricated by coarse abrasive, high contrast sinusoid interference fringe can be achieved because the surface scratches then formed are small in number and large enough to excite mainly one cladding mode to interfere with the core mode. Whereas for smoother SPF by fine abrasive, vast tiny scratches lead to a more complicated multiple interference and then generate the irregular spectrum shown in Fig. (f). Beside high contrast interference fringe, insertion loss is another factor need to be optimized. Insertion loss existing in spectrum is mainly caused by the surface scattering of scratches. For SPF1 and SPF2 fabricated by 800 or 1500-mesh coarse abrasive, the insertion loss is about 10 ~ 20dB. Whereas for SPF3 fabricated by fine 3000-mesh abrasive, the insertion loss is somehow above 30dB due to the contribution of vast tiny scratches to surface scattering. Thus, to realize a higher contrast interference fringe as well as a lower insertion loss, the 800 or 1500-mesh coarse abrasive is a good choice in fabrication.

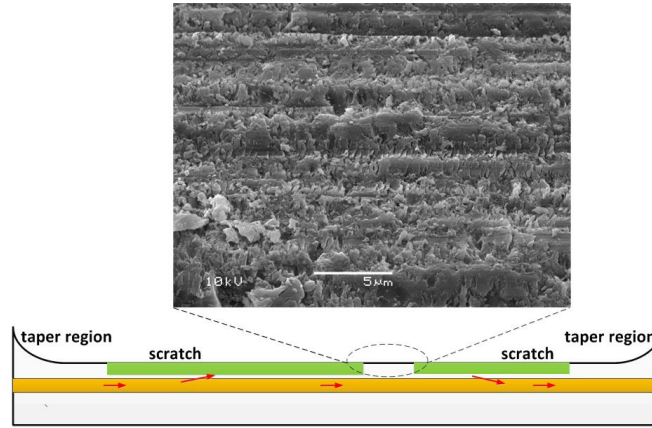


Fig. 4. View of the discontinuous scratches taken by 5000X SEM, and the approximate MZI model for the rough SPF with discontinuous scratches. Yellow: fiber core, White: cladding, Green: surface scratches.

To optimize the polished length of rough SPF, another four SPFs with polished length of 10, 20, 30, and 40mm were fabricated all by 800-mesh abrasive paper respectively. As shown in Fig. 5 (c) and 5 (d), similarly sinusoid interference fringes with contrast ratio around 10 dB were observed in the 30 and 40 mm SPF. Whereas for another two shorter SPFs with polished length of 10 and 20 mm shown in Fig. 5 (a) and 5 (b), interference patterns were too weak to figure out. For SPFs all fabricated by 800-mesh abrasive, length of scratches is mainly determined by the rolling movement of mechanical wheel. Statistically, SPF with long polished length is tend to form the cascade MZI structure shown in Fig. 4, ensuring a enhanced MZI interference profile with higher contrast. However, longer polished length also contributes to a large optical path difference, resulting in a more dense resonance dips and higher insertion loss. As compared Fig. 5 (d) with Fig. 5(c), the resonance dips of 40mm-SPF were more crowded than the 30mm-SPF, and also with higher loss exist in the Fig. 5 (d). So there is a upper limitation for polished length. Empirically, the polished length of the rough-SPF sensor was controlled within 30 to 40 mm in our experiment.

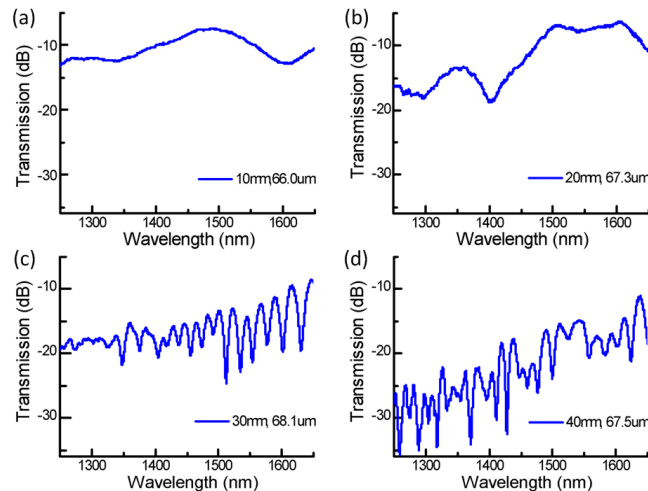


Fig. 5. Transmission profile of four SPFs with different polished length of (a) 10 mm, (b) 20 mm, (c) 30 mm, and (d) 40mm. All SPFs were fabricated by 800-mesh abrasive paper, with the remained fiber thickness of 67.0, 67.3, 68.1, 67.5 μm respectively.

#### 4. Strain and temperature responses

SPF1 illustrated in Fig. 3 (a) was chose to investigate the responses of rough SPF to tensile strain and temperature as example. For strain measurement, one end of SPF1 was fixed and another end was attached to a translation stage with a resolution of 10  $\mu\text{m}$  [14]. A tensile strain was applied to SPF1 by moving the translation stage away from the fixed one. The total length of the stretched fiber was 100 mm. Dip1 and Dip2 illustrated in Fig.3 (d) were measured with the increased tensile strain from 0 to 1000  $\mu\epsilon$  with a step of 100  $\mu\epsilon$ . As the strain applied to the SPF, the difference between the effective refractive index of core and cladding mode changed due to the elasto-optical effect, and the geometry of SPF also deform slightly. As shown in Fig. 6 (a), resonant wavelengths of Dip1 and Dip2 around 1512 nm and 1630 nm shift linearly toward a shorter wavelength, which was mainly caused by the elasto-optical effect, with sensitivity of  $K_{s1} = -1.47 \text{ pm}/\mu\epsilon$  and  $K_{s2} = -2.00 \text{ pm}/\mu\epsilon$  respectively.

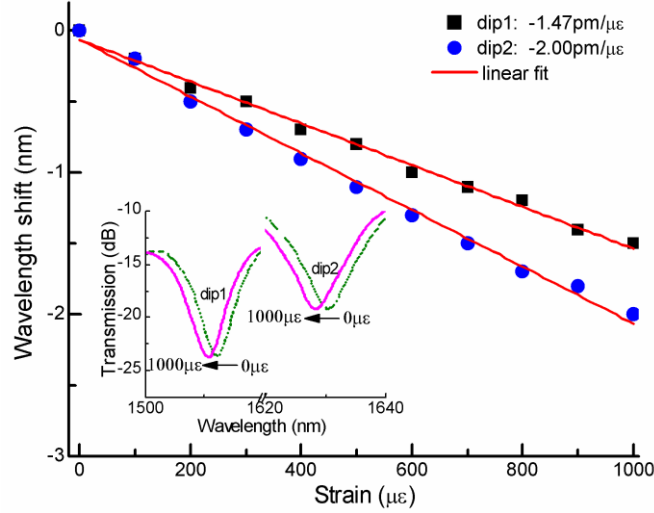


Fig. 6. Wavelength shifts of Dip1 and Dip2 in SPF1's interference fringe in Fig. 3 (d), when tensile strain increases from 0 to 1000  $\mu\epsilon$  with a step of 100  $\mu\epsilon$ .

A column oven (LCO 102, ECOM) with a temperature resolution of 0.1  $^{\circ}\text{C}$  was employed to investigate the thermal response of SPF1 by means of heating it from 30 to 100  $^{\circ}\text{C}$  with a step of 10  $^{\circ}\text{C}$  [15]. At each step, the temperature was stabilized at the target values for 10 min before the spectrum recorded. As shown in Fig. 7, while temperature rose, Dip1 and Dip2 around 1512 nm and 1630 nm shifted linearly toward a longer wavelength due to the thermo-optic effect of the fiber, with sensitivity of  $K_{T1} = 25.32 \text{ pm}/^{\circ}\text{C}$  and  $K_{T2} = 29.37 \text{ pm}/^{\circ}\text{C}$  respectively.

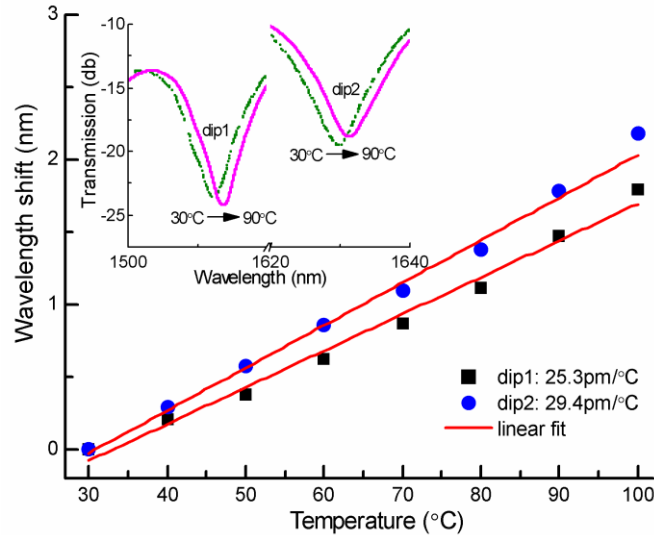


Fig. 7. Wavelength shift of Dip1 and Dip2 in SPF1's interference fringe in Fig. 3 (d), when temperature rose from 30 to 100 $^{\circ}\text{C}$  with a step of 10  $^{\circ}\text{C}$ .

Assuming the wavelength shift induced by strain and temperature approximated as  $y=Kx+b$ , where  $K$  is expressed as the independent temperature sensitivity  $K_{T1}$  and  $K_{T2}$ , or strain sensitivity  $K_{s1}$  and  $K_{s2}$  at each attenuation dips. Combined with the wavelength shift of the two dips  $\Delta\lambda_1$  and  $\Delta\lambda_2$ , the change of strain and temperature  $\Delta S$  and  $\Delta T$ , can be given by the coefficient matrix below [16-17].

$$\begin{bmatrix} \Delta S \\ \Delta T \end{bmatrix} = \begin{bmatrix} K_{s1} & K_{T1} \\ K_{s2} & K_{T2} \end{bmatrix}^{-1} \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \end{bmatrix} = \begin{bmatrix} -1.47 & 25.32 \\ -2.00 & 29.37 \end{bmatrix}^{-1} \begin{bmatrix} \Delta\lambda_1 \\ \Delta\lambda_2 \end{bmatrix}$$



## 5. Conclusion

In summary, the rough SPF with macro scratches on the polished surface can be directly used to develop a promising sensing device. The cladding modes induced by scratches re-couple back into the fiber core and interfere with the core mode, thus Mach-Zehnder interference pattern occur in the transmission spectrum. In order to achieve SPFs with high interference fringe contrast ratio above 10 dB, 800-mesh or 1500-mesh coarse abrasive paper was employed, the remained thickness of the SPF should be controlled between 66 to 68  $\mu\text{m}$ , and polished length should be from 30 to 40 mm. The rough SPF-based sensor exhibited linear response to strain and temperature with sensitivity up to - 2.00  $\text{pm}/\mu\text{m}$  and 29.37  $\text{pm}/^\circ\text{C}$  respectively, which can be used to realize simultaneous strain and temperature measurement. Aiming at the convenient and low-cost sensor application, more other evanescent fiber sensor based on the proposed rough SPF would be researched in next work.

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