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Application of Seven Core Fiber-Based Sensor on Torsion Angle Measurement and Vital Signs Monitoring

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ABSTRACT
Apart from spatial-division multiplexing optical fiber communication system, seven core fiber has been widely investigated for optical fiber sensing application, such as high temperature, strain and vibration sensors. In this work, we further explored the application of seven core fiber on both conventional industry community and popular healthcare area. On one hand, a novel optical fiber torsion sensor was designed using tapered seven core fiber and demonstrated to measure torsion angles with tunable sensitivity, which can achieve as high as 1 nm/°. Moreover, the proposed torsion sensor owns the ability to discriminate the rotation direction with stable performance. On the other hand, based on the interference between the center core and surrounding cores in seven core fiber, an optical fiber interferometer was proposed using conventional sandwich structure to monitor the vital signs and activities of patients on bed. Respiration signals can be obtained and on bed/off bed/body movement activities can be recognized using this seven core fiber-based interferometer.
Keywords: seven core fiber, torsion sensor, optical fiber interferometer, vital signs.

1. INTRODUCTION

To cope with the exponential growth of internet traffic, spatial-division multiplexing (SDM) technique was proposed and corresponding specialty optical fibers were also designed for SDM transmission by using degree of freedom of space in optical fibers [1]. As one of the typical SDM optical fibers, multi core fiber with a few cores in a single fiber was investigated widely and has also been demonstrated as the most potential candidate for future SDM transmission system. Among them, seven core fiber (SCF) is the most popular one since the crosstalk between cores is controllable and analysable considering the complexity of receiver design. Apart from the communication system, SCF was also proposed for optical fiber sensing by using the interaction of different cores. For examples, supermode interference due to the strong coupling in SCF was proposed for high-temperature [2] and strain [3] sensing. Another application of SCF is distributed optical fiber sensing system and both shape [4] and simultaneous temperature and strain [5] can be measured successfully.

In our work, we further developed SCF-based sensors in mechanical parameters measurement and proposed novel torsion sensor based on the inter-core mode coupling in SCF. The torsion sensor was fabricated by tapering the SCF with optimized dimension and splicing single mode fiber (SMF) on both ends. Desirable optical spectrum was achieved for monitoring the wavelength shift with torsion angle and the sensitivities was observed to increase during the fiber twist. In addition, our proposed torsion sensor owns the capability to discriminate rotation orientation and the performance is stable with high accuracy. This SCF-based torsion sensor will be a potential candidate in the applications of structural health monitoring. Other than that, SCF was also utilized in our work for healthcare application, including activities and vital signs monitoring. SCF-based interferometers were designed, fabricated and then packaged under the mattress for non-invasive monitoring. Based on the results, on-bed/off-bed/body movement can be identified by calculating the jitter level of signals while respiration ratio was also obtained from the processed on-bed signal. In summary, SCF shows excellent performance in optical fiber sensing communities, including traditional civil engineering and novel healthcare applications, which pushes forward the further investigation of its based sensor development.

2. TORSION SENSOR BASED ON SEVEN CORE FIBER

The torsion sensor based on SCF was fabricated by splicing two SMFs on both ends of tapered SCF, the schematic of which is shown in the insets of Fig. 1. A CO_2 glass-processing machine (LZM-100, Fujikura) is used for taper structure fabrication and SCF here is commercially available from YOFC in China. To obtain a desirable spectrum for torsion sensing, dimension of the taper needs optimized, including the waist diameter and length. Thanks to the programmable laser power and motor speed inside the LZM-100, we fabricated batches of tapers on SCF with different waist diameters and lengths and summarized the spectrums as Fig. 1. It can be seen that the spectral extinction ratio increased with reduced diameter while fringe spacing decrease with the length. Considering the strength of taper, we finalized the dimension of taper on SCF to be 30 μm of waist diameter, 5 mm of waist length and 5 mm of transition length.

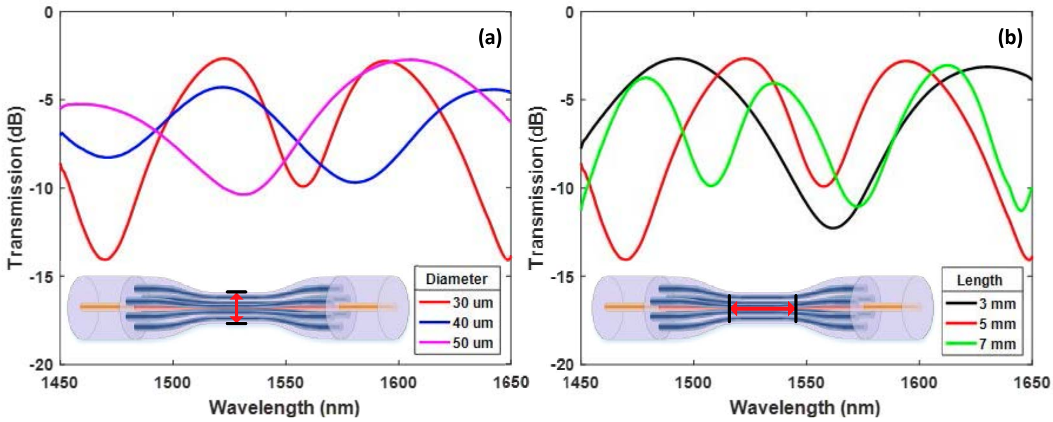

Figure 1. Transmission spectra of the torsion sensors with different waist diameters (a) and waist lengths (b).

The torsion sensing experimental setup is shown in Fig. 2, in which the left holder was fixed while right holder was rotated. The alignment beforehand was conducted to avoid any radial displacement during twisting. Fiber twist angle varied from 0° to 900° with a step of 20° and corresponding spectrum was recorded for further analysis.

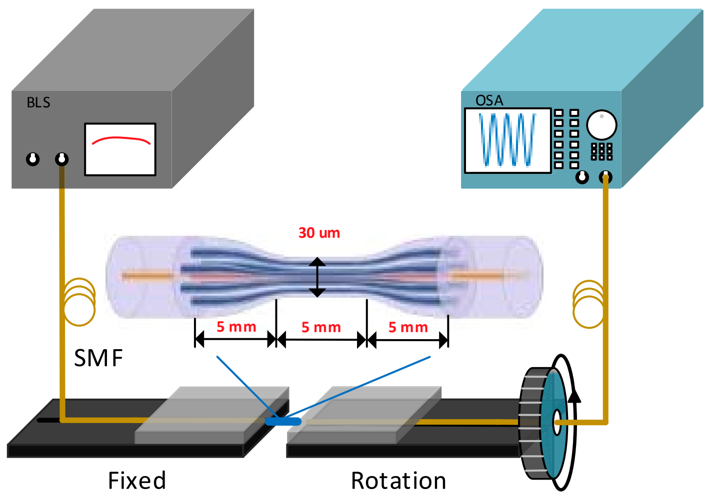

Figure 2. Experimental setup to measure the torsion angle based on tapered SCF.

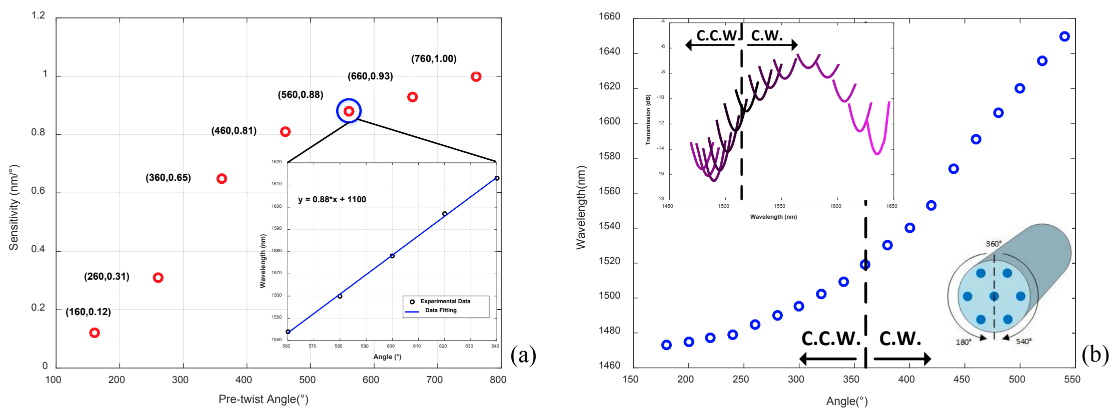

Figure 3. Summarized torsion sensitivities in measurement ranges with different pre-twisting angles (a) and results of rotation direction discrimination (b).

2.1 Tunable sensitivity

To discuss the torsion sensitivity, we pre-twist the sensor with different angles from 160° to 760° and further rotate it within 90° under every per-twist angle. Relatively linear response was considered in every region in order to calculate the sensitivity. The summarized sensitivity in every region with different pre-twist angle was shown in Fig. 3(a). It can be clearly seen that the sensitivity increases with the fiber twist and achieves as high as 1 nm/°.

2.2 Rotation direction discrimination

To verify the ability of torsion sensor to discriminate rotation direction, we pre-twist the fiber to 360° and further rotate it to 540° in clockwise direction and 180° in counter-clockwise direction. The recorded wavelength shift were shown in Fig. 3(b). Thus, we can conclude that the direction can be distinguished by monitoring the wavelength shift direction of red or blue.

2.3 Repeatability

In respective of mass production of optical fiber sensors, repeatability needs to be concerned. We followed the same dimension of taper as inset of Fig. 2 and fabricated batches of sensors. To obtain the accuracy, on one hand, three sensors with same dimension were fabricated and wavelength shift results were recorded as shown in Fig. 4(a). On the other hand, torsion angle measurements were conducted three times using one sensor, the results of which was summarized in Fig. 4(b). Both the largest errors in terms of wavelength shift are 2 nm and corresponding accuracy can be calculated to be ±1° under sensitivity of 0.85 nm/°.

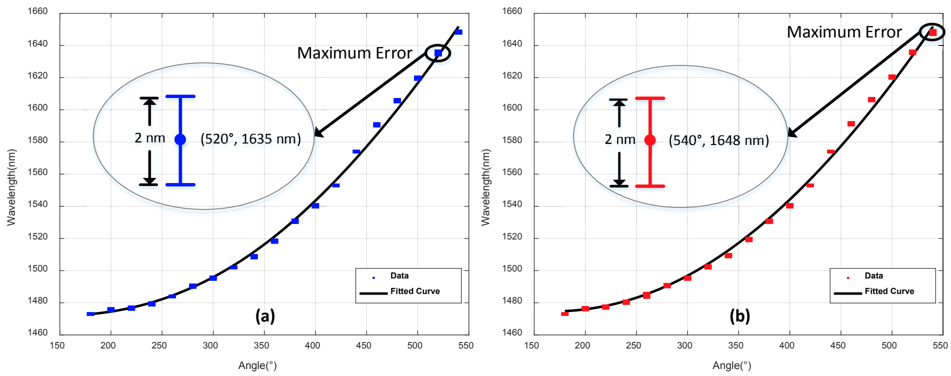

Figure 4. Discussion on repeatability of torsion sensors.

3. ACTIVITIES AND VITAL SIGNS MONITORING USING SCF INTERFEROMETERS

Healthcare application of SCF-based sensors was investigated in this part, including activities and vital signs monitoring. The SCF-based sensor is one kind of traditional interferometer based on sandwich structure: single more fiber-multi mode fiber-seven core fiber-multi mode fiber-single mode fiber (SMF-MMF-SCF-MMF-SMF), which was shown in Fig. 5(a). The MMF was utilized here to excite all the cores in SCF so that the interference between center core and outer cores was formed. The experimental setup was shown in Fig. 5(b). SCF-based interferometer was placed under the mattress in order to realize non-invasive human physical activities and vital signs monitoring. The results were summarized as follows.

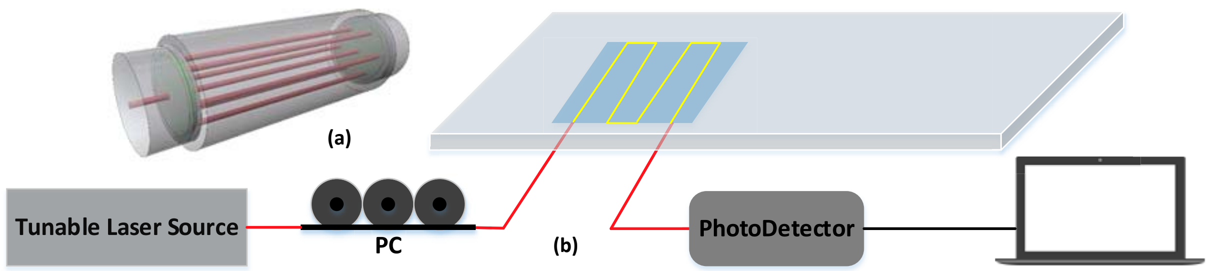

Figure 5. Structure of SCF-based interferometers (a) and the experimental setup (b).

3.1 Activities monitoring

Figure 6(a) shows the signals of three human physical activities: on-bed, off-bed and body movement. It can be seen that the signal jitters are totally different. Thus, with jitter level calculation method, three activities can be identified successfully, the results of which are shown in Fig. 6(a).

3.2 Vital signs monitoring

Time-dependent oscillation can be seen in on-bed signal. The frequency can be obtained by applying FFT on the data sequence. The results were shown in Fig. 6(b), in which the frequency corresponds to the respiration rate of the subject on bed. Thus, other than human physical activities, respiration ratio can also be obtained non-invasively using SCF-based interferometers.

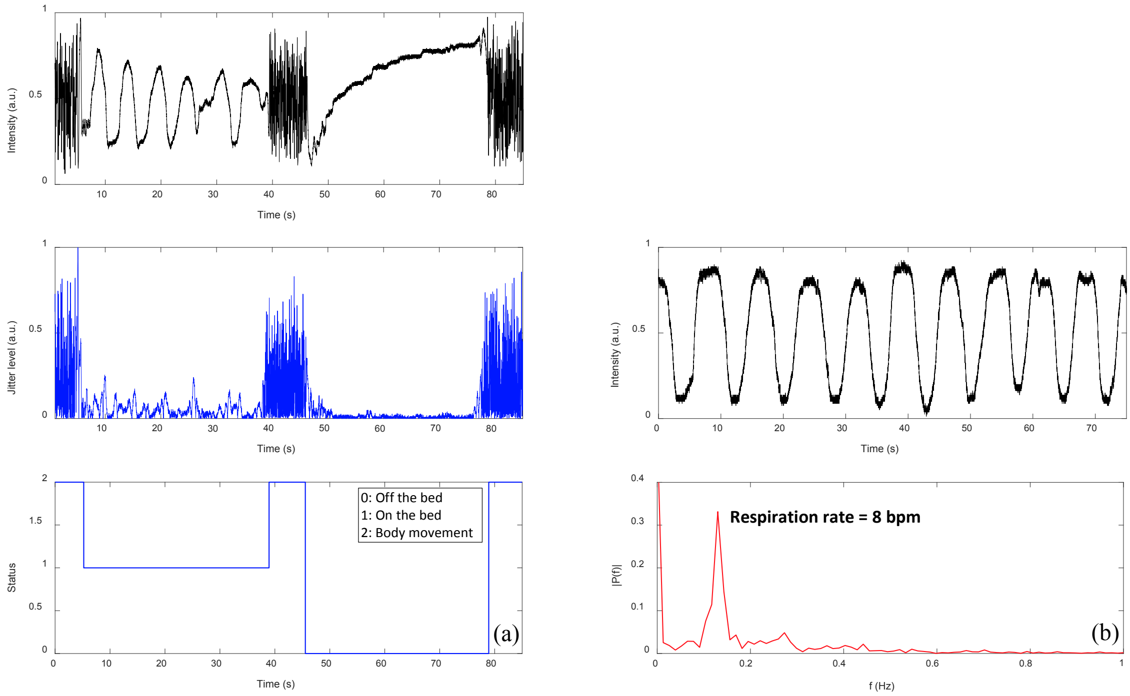

Figure 6. Human physical activities (a) and vital signs (b) monitoring.

4. CONCLUSIONS

To conclude, SCF-based sensors were investigated in this paper, including torsion angle measurement and vital signs monitoring. The proposed torsion sensor was based on easily fabricated taper structure on SCF and its corresponding dimension was optimized. The sensitivity can be tuned by pre-twisting the tapered SCF to different angles and the highest can achieve 1 nm/°. In addition, the torsion sensor is able to distinguish rotation direction and the accuracy can achieve ±1°. On the other hand, SCF was employed for interferometer fabrication for activities and vital signs monitoring. On-bed, off-bed and body movement can be identified, and respiration ratio can be obtained non-invasively. SCF was demonstrated to be a good candidate on current sensing communities and may find further applications in near future.

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