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Optical curvature sensor with high resolution based on in-line fiber Mach-Zehnder interferometer and microwave photonic filter

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Abstract: Curvature measurement plays an important role in structural health monitoring, robot-pose measuring, etc. High-resolution curvature measurement is highly demanded. In this paper, an optical curvature sensor with high resolution based on in-fiber Mach-Zehnder interferometer (MZI) and microwave photonic filter (MPF) is proposed and experimentally demonstrated. The in-fiber MZI is constructed with a ring-core fiber (RCF) which is fusion spliced between two coreless fibers (CLFs). The structure of CLF-RCF-CLF is then sandwiched between two segments of single-mode fiber (SMF), making the whole interferometer structure of SMF-CLF-RCF-CLF-SMF. The operating principle is that different curvatures will cause the variations of the interference spectrum of MZI due to elastic-optic effect, and then the variations are converted into the frequency-shift of the MPF. The factors affecting the visibility of the interference spectrum are researched. A preliminary exploration of the multiplexing demodulation for the in-fiber-MZIs is also investigated and discussed, which is for the first time to the best of our knowledge, holding great potential to pave the way for constructing the sensing network composed of interferometric sensors. The curvature measurement sensitivity is $-147.634 \text{ MHz/m}^{-1}$, and the resolution is $6.774 \times 10^{-6} \text{ m}^{-1}$ which is the highest value up to now.

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1. Introduction

Optical fiber sensors have the advantages of small size, light weight, electromagnetic interference resistance, environmental corrosion resistance, etc., and have been widely studied and applied in recent decades, such as measuring strain [1], bending [2,3], temperature [4], curvature [5] and so on. Curvature is a crucial parameter in many fields, such as structural health monitoring [6], medicine [7], robot's posture measurement [8], etc. In June 2021, China's Shenzhou XII spacecraft successfully launched into space carrying a seven-degree-of-freedom robotic arm that will perform high-precision mechanical movements in space, which also presents a potential need for the high-resolution measurement of the curvature in the aerospace field.

The reported optical fiber curvature sensing schemes could be divided into three categories: the distributed curvature sensing [5,9,10], the quasi-distributed curvature sensing [11], and the

point curvature sensing [12–25]. The distributed curvature sensing schemes are mainly dependent on the technology of Brillouin optical time-domain analysis (BOTDA) [5,9] or Brillouin optical time-domain reflectometry (BOTDR) [10], and more than one laser and expensive high-frequency signal generator are needed in the system. Furthermore, any jitter of the laser may cause the distortion of the optical pulse in the system and result in the measurement failure. The quasi-distributed curvature sensing relies on the fiber Bragg grating (FBG) array, which is inscribed in a special multi-core optical fiber with a length of tens of meters [11]. The former two schemes are suitable for some specific application scenarios, and the systems are complex and expensive. The point curvature sensing scheme has wider application prospect and attracted much more attention in recent years. The point curvature sensors mainly include three types: the in-fiber MZI [12–17], the FBG [18,19], and the LPG [20,21]. The TFBG [22] and FP [23,24] are also reported. Among them, the in-fiber MZI has been widely researched for its advantages of easy fabrication, high reproducibility, and moderate robustness. However, most of the reported in-fiber-MZI based curvature sensors have relative low resolution due to the demodulation in optical domain, which is mainly limited by the hardware of the optical spectrum analyzer (OSA). This will severely limit the application of the optical fiber curvature sensor in some high-resolution needed scenarios.

Microwave photonics (MWP) is an interdisciplinary field combining the microwave engineering and the optoelectronics, which has attracted more and more attention in recent years [26,27]. With the development of the MWP technology, optical fiber sensors based on MWP are also proposed [28–30]. These types of sensors have the inherent advantages of high resolution, fast speed, high stability, and good robustness to environments changes [28]. The characteristic of high resolution is produced by the huge frequency difference between the optical signal and the microwave signal, and any slight fluctuation of the wavelength in the optical domain will be converted into large fluctuation of frequency in the microwave domain through the wavelength-to-frequency mapping mechanism [31]. Optical sensors based on MWP are mainly constructed based on technologies of the microwave photonic filter (MPF) [28,32–34] and the optoelectronic oscillator (OEO) [29,35–37]. The sensors based on MPF have been widely reported because of the simple demodulation structure.

In this paper, we propose and experimentally demonstrate a high-resolution optical curvature sensor based on the in-fiber MZI and the MPF technology. This work is mainly inspired by [38] and [5]. Reference [38] presents an optical spectrum slicing technology, which can be utilized to construct a single-passband fiber. Reference [5] demonstrates that the ring-core fiber (RCF) has the characteristics of confine the light transmitting in the ring core even when the fiber is bending, which shows the potential good capability of the ring core in fiber to work as the reference-arm of the MZI. The in-fiber MZI here is constructed with the structure of SMF-CLF-RCF-CLF-SMF, where the SMF means the single mode fiber and the CLF means the coreless fiber. The contrast of the interference spectrum is up to 23.018 dB, and the measured sensitivity is $-147.634 \text{ MHz/m}^{-1}$. The resolution is $6.774 \times 10^{-6} \text{ m}^{-1}$, which is the highest value up to now and is 1~3 orders of magnitude higher than the reported curvature sensors [12–17]. It also shows much simpler fabrication requirement and better mechanical robustness than [12,15,16] and [14], respectively. We make an experimental analysis of the factors that affecting the visibility of the MZI interference spectrum. Furthermore, a preliminary exploration of the multiplexing demodulation for the in-fiber-MZI-sensors is also investigated, which is the first time to the best of our knowledge to discuss the multiplexing capability of the in-fiber-MZI sensors combining with the MPF technology. The proposed sensor has the potential in applications where the resolution of curvature sensing is highly demanded.

2. Principle and experimental setup

Figure 1(a) shows the section-structure along the axis of the proposed in-line fiber MZI and Fig. 1(b) shows the end face of the RCF scanned by the electron microscope. The structure of the RCF can be divided into three parts, and from the outside to the inside is: the cladding, the ring core, and the silica layer in the center. The measured outer-diameter of the ring-core is $15\ \mu\text{m}$, the diameter of the silica layer in the center is $7.04\ \mu\text{m}$, and the diameter of the cladding is $125\ \mu\text{m}$. The refractive indices of the cladding and the ring core are 1.4597 and 1.4728, respectively. It should be noted that the silica layer in the center has the same refractive index with the cladding. Here, the interference modes of the two arms of the proposed MZI are composed of the core mode and the cladding mode of the ring core fiber, respectively. The mode in the center silica layer is equivalent to the cladding mode. The light transmitted in SMF is split into two beams by the CLF firstly. One beam transmits through the ring core acted as the reference signal in the MZI. The other passes the cladding and the central silica layer. Then, these two beams couple into one beam in the second CLF and transmit through the SMF. The CLFs play a role of beam splitter and coupler respectively, which is illustrated with label 'L1' and 'L3' respectively in Fig. 1(a). L1, L3 are the length of the CLF, and L2 is the length of RCF.

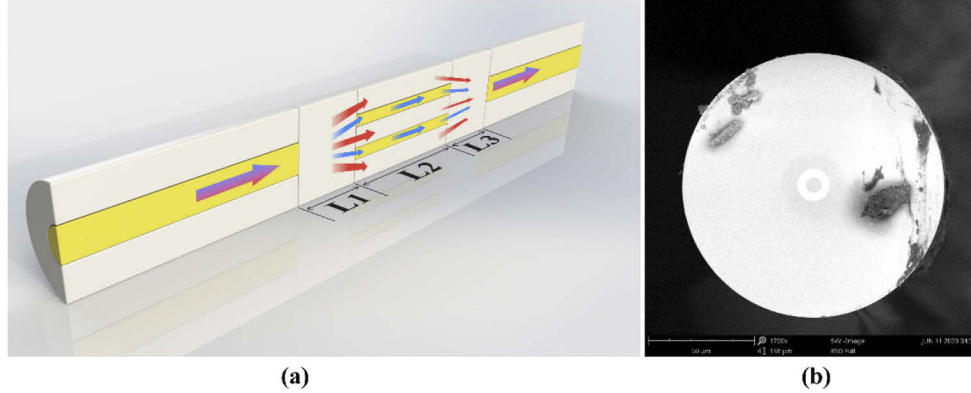


Fig. 1. The section-structure along the axis of the designed in-line fiber MZI (a) and the end-face of the RCF (b).

The output intensity of the MZI at a given wavelength is written as [2]:

$$I = I_1 + I_2 + 2\sqrt{I_1 I_2} \cos(\Delta\varphi), \quad (1)$$

$$\Delta\varphi = 2\pi\Delta n_{\text{eff}}L/\lambda \quad (2)$$

$$V = (I_{\text{max}} - I_{\text{min}})/(I_{\text{max}} + I_{\text{min}}) \quad (3)$$

where I_1 and I_2 are the intensities of two interference modes; $\Delta\varphi$ is the phase difference between both modes; L is the length of the RCF fiber for the proposed curvature sensor; V is the visibility of the MZI; I_{max} and I_{min} are the maximum and minimum values of intensity respectively.

Figure 2 shows the experimental layout of the in-fiber MZI sensor for the curvature measurement. Three three-dimensional displacement stages (3D-stages) are used. The top surfaces of the left and the right stages are set at the same horizontal height, and the distance between them is $2s$. The MZI-sensor is fixed to bottom surface of a steel ruler with the UV glue. The ruler is fixed to these two stages with the steel screws. A steel cylinder with a small diameter ($\sim 2\ \text{mm}$) is fixed on the third stage that is in the middle of the former two stages. By moving the middle stage up and down in the vertical direction (Z direction in the figure), the upper surface without the sensor attached will be moved accordingly by steel cylinder, resulting in different curvatures. The

moved distance of the ruler in vertical direction is h . The curvature of the MZI-sensor can be written as [13]:

$$C = \frac{1}{R} = \frac{2h}{h^2 + s^2} \quad (4)$$

Figure 3 shows the experiment setup of the proposed curvature sensing system. The amplified spontaneous emission (ASE) light source works as a broadband source with the operating wavelength of 1527nm~1565nm. There are two erbium-doped fiber amplifiers (EDFAs), and one of them is the boost-type EDFA1, which is used to increase the optical power to the subsequent optical path. The other is the pre-type EDFA2 to amplify the weak optical signal. The light output from the EDFA1 is sent into the in-fiber-MZI sensor (S1) which is utilized to slice the broadband spectrum. S1 is used for the curvature sensing. The light with the sliced spectrum passes through the fiber coupler (FC, 90:10), and the 90% of the light is sent into the electro-optical modulator (EOM, MXAN-LN-40) to work as optical carriers. The other 10% is observed by the optical spectrum analyzer (OSA, AQ6370D). The modulated optical signals pass through the dispersion compensating fiber (DCF, -497ps/nm) to realize the wavelength to time mapping. Then the optical signals are amplified by EDFA2 and recovered into the radio frequency (RF) signals by the photodetector (PD, Conquer KG-PT-40G). The ASE, EDFA1, S1, FC, EOM, DCF, EDFA2 and PD together constitute the microwave photonic filter (MPF). The vector network analyzer (VNA, Keysight E5071C) is used to measure the response of the MPF.

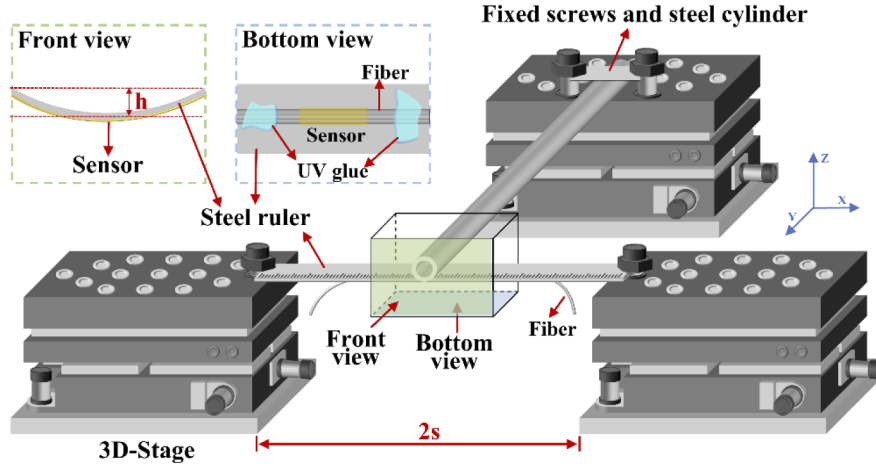


Fig. 2. The schematic diagram for the curvature measurement.

The transfer function of the in-line fiber MZI can be expressed as [38]:

$$T_{MZI}(\omega) = \frac{1}{2} \left[1 + V \cos \left(2\pi \frac{\omega}{\Delta\omega} \right) \right] \quad (5)$$

where $\Delta\omega = 2\pi c/L_{OPD}$ is the free spectrum range (FSR) of the MZI, which is decided by the optical path difference L_{OPD} of the two arms of MZI; c is the speed of light in vacuum.

The frequency response of the MPF based on spectrum sliced technology can be expressed as [38,39]:

$$H_{RF}(\Omega) = \int S(\omega) \cdot T_{MZI}(\omega) [H^*(\omega) \cdot H(\omega + \Omega) + H(\omega)H^*(\omega - \Omega)] d\omega \quad (6)$$

where Ω is the angular frequency of the RF signal that is used to modulate the EOM, $S(\omega)$ is the spectrum of the ASE, and $H(\omega) = |H(\omega)| \cdot e^{-j\theta(\omega)}$ is the transfer function of the DCF. The

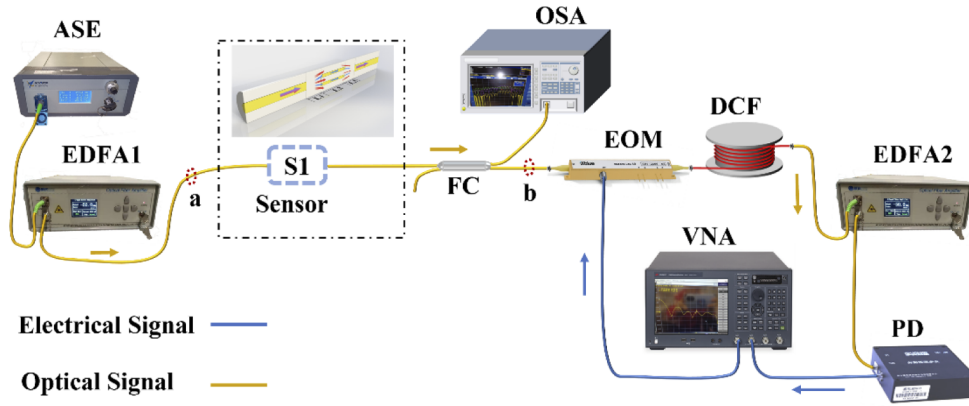


Fig. 3. Experimental system setup.

frequency response of this type of MPF is typically a single-passband filter in RF field. The central frequency of the passband can be expressed as:

$$f_c = \frac{1}{D \cdot \Delta\omega} = \frac{L_{OPD}}{D \cdot 2\pi c} \quad (7)$$

Also, $f_c = 2\pi/\Omega$. D is the dispersion value of the DCF. The variation of the optical path difference of the fiber based MZI can be caused by the thermo-optic effect, thermo-expansion effect, and elastic-optic effect. For the measurement of curvature, elastic-optic effect plays the dominant role. Thus, the variation of the optical path difference can be written as:

$$\Delta L_{OPD} = L_{OPD0} \cdot (1 - p_\epsilon) \cdot k \cdot C \quad (8)$$

where the L_{OPD0} is the initial optical path difference value when the in-fiber MZI is without curvature applying. p_ϵ is the elastic-optic coefficient; k is a constant related to the material and the structure of the MZI, and C is the measured curvature. Combining formula (7) and (8), the relationship between the frequency shift of the passband in RF field and the measured curvature can be expressed as:

$$\Delta f_c = \frac{L_{OPD0} \cdot (1 - p_\epsilon) \cdot k \cdot C}{D \cdot 2\pi c} \quad (9)$$

3. Experimental results and discussion

3.1. Curvature measurement

The characteristics of the in-fiber-MZI sensor is researched firstly to provide a valuable guidance for the subsequent work. More than twenty sensors with different lengths of CLF and RCF are made in the experiment, and eight representative sensors among them are listed here for comparative illustration. Figure 4 shows the measured interference spectrum of the eight lab-made sensors. Table 1 lists the parameters of the sensors which are named No.1~No.8. It can be seen from Table 1 that the change trend of the visibility is consistent with that of the contrast. When the contrast is large, the corresponding visibility is also large. To investigate the sensing performance of the sensors and to ensure the system has a better signal-to-noise ratio simultaneously, the No.8 sensor that with a moderate contrast is chosen to measure the curvature.

The No.8 sensor is work as the 'S1' in Fig. 3. The measured contrast of the No.8 sensor is 21.134 dB, which is not the highest value among the sensors. Noted that the listed values of the

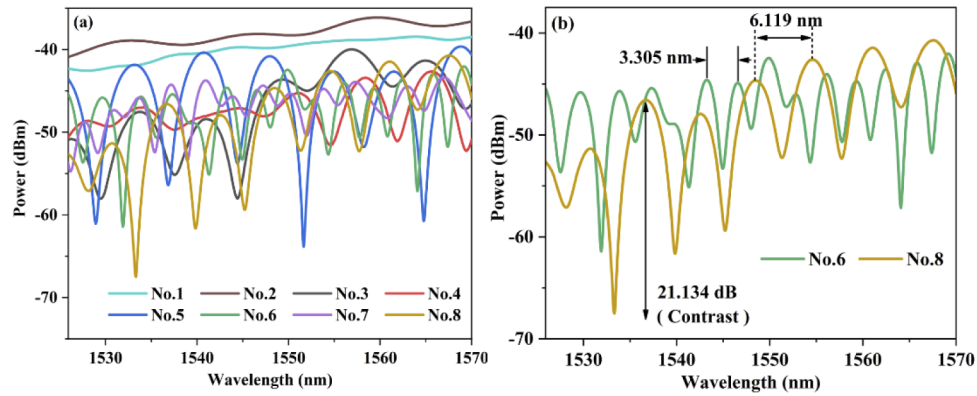


Fig. 4. Measured interference spectrum of the eight lab-made sensors (a) and the spectrum of the selected two sensors used in the experiment (b).

Table 1. Parameters of the lab-made sensors

Number (sensor)	L1 (CLF) (mm)	L2(RCF) (mm)	L3(CLF) (mm)	Contrast (dB)	Visibility (maximum)	FSR (nm)
No.1	0	32	0	-	-	-
No.2	0	18.5	0	~2.185	~0.246	~13.153
No.3	1	26	1.4	14.494	0.932	7.677
No.4	~0.3	30	1	8.259	0.740	7.285
No.5	1.5	31	1	23.018	0.990	7.224
No.6	0.5	61.5	0.5	15.744	0.948	3.505
No.7	0.5	60	0.5	9.932	0.815	3.645
No.8	1	32	1.5	21.134	0.985	6.119

contrast and the visibility are the measured maximum values in the C-band. The measured FSR value that near the 1550 nm of the No.8 sensor is 6.119 nm.

By comparing the measured parameters shown in Table 1, we can also find that the visibility is affected by the lengths of the RCF and the CLF. The longer the RCF is, the worse the visibility will be. The worse visibility can be explained: with the length of the RCF increasing, the optical power in the cladding will decrease, while the power in the ring core is almost the same. Thus, the power-imbalance between the ring core and the cladding deteriorates the visibility. The length of the CLF is recommended to be 1~1.5 mm and the detailed analysis is presented in the following discussion section. In addition, the insertion loss of the sensors is also related to the length of the RCF and the CLF. For example, the measured insertion losses of sensors No.1 ~No.4 and No.8 are 5 dB, 3.9 dB, 13.7 dB, 15.3 dB, and 16.53 dB, respectively.

In the experiment, the distance value $2s$ between the two 3D-stages in Fig. 2 is set as 17.5 cm. The vertical moving distance h is obtained by adjusting the z-axis knob of the middle 3D-stage. More specifically, the step of adjusting the knob is set as 20 degrees each time, and 50 degrees correspond to a vertical movement of 0.5 mm. Then, the different curvatures can be obtained according to formula (4). The measured amplitude-frequency response of the MPF is shown in Fig. 5(a). The center frequency of the passband is chosen as the tracking signal to evaluate the variation of curvature. To improve the measurement accuracy, we firstly use the 'peak search' function of the VNA to mark the peak position of the passband. Then, during the processing of the experimental data, the two cut-off positions corresponding to 3 dB bandwidth is located, and the center frequency of the passband should be in the center of the two positions.

The measurement accuracy could be improved by comparing these two measured results. The corresponding fitting result of the measured data is shown in Fig. 5(b) which shows a linear relationship between the curvature and the frequency. The measured sensitivity is $-147.634 \text{ MHz/m}^{-1}$. Considering the bandwidth of the intermediate frequency (IF) filter of the VNA is set as 1 kHz in the experiment, the resolution of the measurement is $6.774 \times 10^{-6} \text{ m}^{-1}$. The measured curvature range is $0 \sim 0.783 \text{ m}^{-1}$.

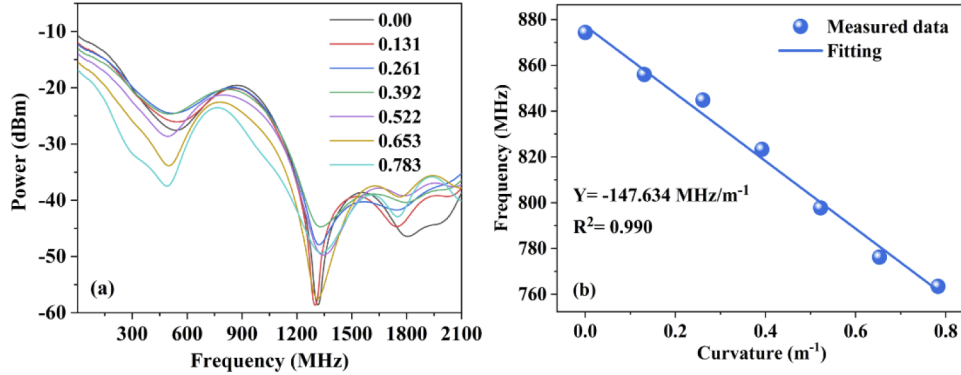


Fig. 5. Measured frequency response of the MPF with different curvatures (a), and the corresponding fitting result (b).

To investigate the repeatability of the curvature measurement, three rounds of measurements are carried out: the steel ruler is pressed down in the 1st round, then the ruler is raised in the 2nd round, and finally the ruler is pressed down again in the 3rd round. It can be seen from the Fig. 6(a) that the three-rounds measurements show a relatively good repeatability. The maximum deviation of the three repeated measurements is $\sim 6.383 \text{ MHz}$, which corresponds to the third measuring point of the curvature. Considering the measured curvature sensitivity $-143.352 \text{ MHz/m}^{-1}$, the corresponding maximum curvature error of the repeatability is 0.0445 m^{-1} , and this maximum deviation is relatively small and acceptable. Figure 6(b) shows the corresponding fitting result of the measured average frequency values of the three measurements with the curvatures. The error bars in Fig. 6(b) show the standard deviations of the measured average values, and the maximum standard deviation is 3.478 MHz corresponding to the measuring curvature of 0.261 m^{-1} . The minimum standard deviation is 1.596 MHz corresponding to the curvature of 0.783 m^{-1} . To further improve the repeatability of the measurement, the sensor could be packaged more appropriately. For example, the steel ruler could be replaced with a metal strip of memory alloy which is more responsive to the deformation. In addition, a more viscous fixator could be used to wrap the whole sensor with the metal strip, which would further improve the whole repeatability.

3.2. Preliminary validation of the multiplexing demodulation capability

In some application scenarios, only one single in-fiber-MZI sensor cannot meet the practical requirements, such as the requirement of multi-point curvature measurement, or the requirement of simultaneous measurement of the curvature and the temperature or other parameters. The sensing system needs to have a certain multiplexing capability. Therefore, we preliminarily explore the multiplexing demodulation capability.

Here, two sensors (S1 and S2) are multiplexed within the proposed system to verify the function. As shown in Fig. 7, sensors S1 and S2 form a parallel structure, and this structure is used to replace the sensing part in Fig. 3. The positions marked with 'a' and 'b' in Fig. 7 correspond to positions with the same markers in Fig. 3, respectively. The S1 remains corresponding to the

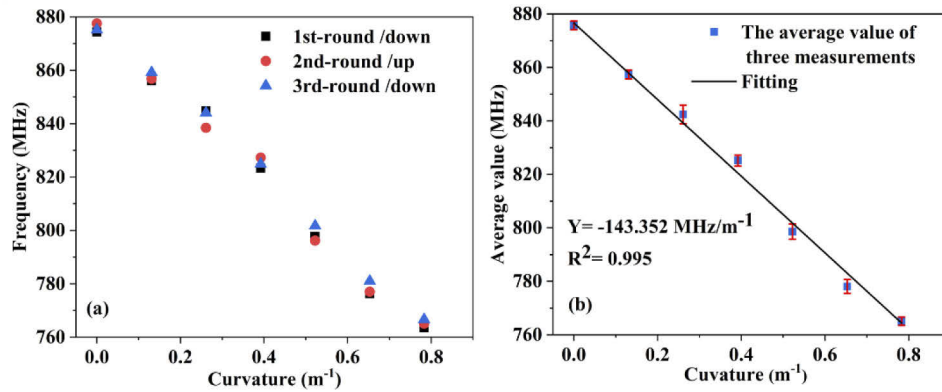


Fig. 6. Repeatability verification with three-rounds measurements (a), and the fitting relationship between the average values of three measurements of the frequency and the corresponding curvatures (b).

No.8 sensor and keeps the function of measuring the curvature, while the S2 corresponds to the No.6 sensor is used to measure the temperature. The measured initial frequency response is shown in Fig. 8(a). Obviously, there appears two passbands. The passband1 is corresponding to the response of sensor S1, and the passband2 is to the response of sensor S2. There is no obvious overlap between the two passbands. This is consistent with the prediction of Formula (7). More specifically, different values of $\Delta\omega$ (FSR) will correspond to different frequency values f_c . Here the FSR value of S1 is 6.119 nm, and the FSR of S2 is 3.326 nm. The former value is nearly double than that of the latter, which ensures that the two passbands in the frequency domain do not overlap.

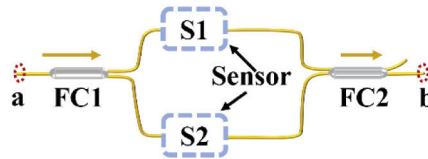


Fig. 7. Two sensors with parallel structure to verify the multiplexing capability.

The sensor S2 is placed in the thermostat with the temperature increasing from 25°C to 27°C, and the step is 1°C. The central frequency of the passband2 is chosen as the tracking signal to evaluate the variation of temperature. The variations of the passband2 are shown in the inset in Fig. 8(b), which shows the relationship between the measured frequency and the temperature. The center frequency of passband1 is almost constant when S2 measures the temperature. The experimental results in Fig. 8 prove the multiplexing demodulation capability of the system.

3.3. Discussion

Three aspects related to the performance of the proposed sensor are specifically discussed and compared here. Firstly, the factors affecting the visibility of the interference spectrum of the sensor are analyzed, because the visibility will affect the response of the MPF, as shown in formula (6). By analyzing parameters in Table 1, we can find that when there is no CLFs to work as the beam splitter or beam coupler, no obvious interference spectrum (sensor No.1) or poor visibility (sensor No.2) appears. Furthermore, when the length of CLF is shorter than or equal to 0.5 mm, the effects of beam splitter and beam coupler are not ideal and the visibility is not

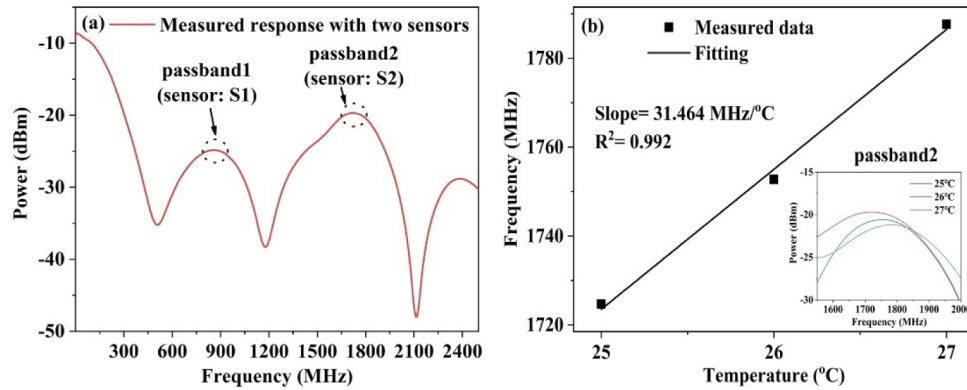


Fig. 8. The frequency response of the system when two sensors (S1, S2) are operating simultaneously (a), and the fitting result of temperature-frequency measured by the S2 (b).

optimal, such as the sensor No.4 and No.7. In the experiment, we also find that the visibility of the interference spectrum deteriorates when the length of the CLF exceeds 2 mm. Therefore, the roles of the beam splitter and coupler, which like the CLFs playing in this design, is necessary when designing such in-line-fiber-MZI sensors. The ideal length of CLF is recommended to be 1~1.5mm, as shown in the sensor No.5 and No.8. It should be noted that the length parameters of CLFs and RCFs that we discuss are for the case where it is easy to make by hand, not for the completely idealized case. The measured parameters that shown in Table 1 also indicate the reproducibility of the fabrication.

Secondly, the multiplexing demodulation capability of the system can be further optimized. To avoid the overlap of the two passbands in the frequency domain, the enough difference between the FSR values of S1 and S2 in optical domain is needed. However, the large FSR difference in optical domain will cost a large spectrum resource, which is not conducive to the multiplexing of the sensors. This method is only suitable for the multiplexing of a few sensors. At the same time, according to formula (7), increasing the dispersion D can also have an equivalent effect. An effective method is to optimize the structural design of the system. The time division multiplexing (TDM) technology can greatly improve the multiplexing demodulation capability of the system. The expected and optimized design scheme is shown in Fig. 9, and the further verification will be carried out in the future. The time controller here is used to assist the TDM function. The total multiplexing capacity of the scheme is M times N .

Thirdly, the measurement range of the proposed sensor is discussed. It is found in the experiment that when the applied curvature is too large, the visibility and even the whole optical interference waveform are seriously deteriorated. The corresponding bandpass waveform of the filter's response is also seriously deteriorated. This is because when the in-fiber-MZI sensor is bent to a certain extent, part of the light energy leaks out, such as leaking into the higher-order cladding. The measured curvature range in the experiment is 0~0.783 m^{-1} . When considering multiple sensors working simultaneously, the measurement range is also limited by the frequency-space between the two adjacent passbands of the response of the filter, which can be explained by Eqs. (7)–(9). Thus, there is a trade-off between the measuring range and the sensitivity. The high sensitivity of the sensor will produce large frequency shift of the passband, while the two adjacent passbands cannot overlap. Therefore, when multiple sensors are multiplexed in the system, the theoretical measurement range is equal to the frequency interval between the two adjacent passbands divided by the sensitivity.

Compared with the reported sensors, the proposed sensor has the advantages of high resolution, easy fabrication, and moderate robust structure. It is suitable for the scenarios with high

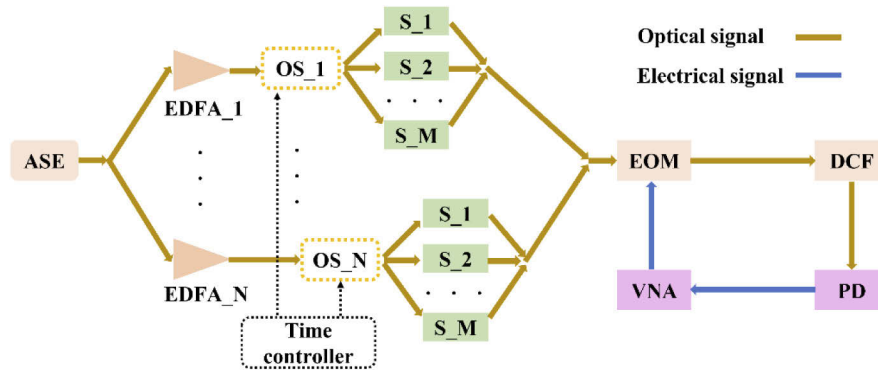


Fig. 9. The expected and optimized design scheme. OS: optical switch; the number N and M are positive integers.

requirements on the above three advantages. Specific comparisons between the proposed sensor and parts of the references are shown in Table 2. The listed resolution is calculated by dividing the instrument's resolution by the measured sensitivity. It should be noted that highest measuring-resolution capability of the OSA is considered in the comparison, with the wavelength resolution is 0.02 nm and the corresponding power resolution is 0.001 dB. It also can be found in Table 2 that the resolution of our proposed sensor is the highest, which is 1~3 orders of magnitude higher than that of most reported sensors.

Table 2. Comparison between the proposed sensor and parts of references

Ref	Sensor	Structure	Sensitivity	Measurement range (m^{-1})	Resolution (m^{-1})
[14]	in-fiber MZIs	2-parallelized 2-core MZIs	$214.533 \text{ nm/m}^{-1}$	0.3~0.8	9.323×10^{-5}
[15]	in-fiber MZI	2-segments of asymmetric 3-core fibers	4.66 dB/m^{-1}	0~0.159	2.146×10^{-4}
[16]	in-fiber MZI	4 up-tapers in series	4.362 nm/m^{-1}	0~1.134	4.585×10^{-3}
[21]	LPGs	3-different LPGs in 7-core fiber	-4.85 nm/m^{-1}	0~1.77	4.124×10^{-3}
[18]	FBGs	FBGs in multicore fiber	92 MHz/m^{-1}	0~4.8	1.087×10^{-5}
[24]	FBG-FPs	FBG-FPs in 2-core fiber and SMF	-1.19 GHz/m^{-1}	0.17~0.43	8.2×10^{-5}
[22]	TFBG	TFBG in multicore fiber	70 pm/m^{-1}	0~4	0.286
This work	in-fiber MZI	CLF + RCF + CLF fusion spliced with SMFs	$-147.634 \text{ MHz/m}^{-1}$	0~0.783	6.774×10^{-6}

4. Conclusion

In conclusion, we have proposed and experimentally demonstrate an optical curvature sensor with high resolution that based on a new designed in-fiber-MZI-sensor head and the microwave

photonic filter technology. The sensor-head is constructed with the structure of SMF-CLF-RCF-CLF-SMF. Firstly, the visibility of the interference spectrum is found to be affected by the lengths of the CLF and RCF by the experimental comparison. The measured maximum visibility is up to 0.990. Secondly, a high-resolution-curvature-sensing capability is obtained by utilizing the microwave photonic filter technology to demodulate the designed in-fiber-MZI-sensor head. The measured sensitivity is $-147.634 \text{ MHz/m}^{-1}$, and the resolution is $6.774 \times 10^{-6} \text{ m}^{-1}$ which is the highest value up to now. Thirdly, the multiplexing demodulation ability of this MPF-based scheme applying to the pure in-fiber-MZI kind sensors is explored experimentally and discussed, which is the first time to the best of our knowledge. The expected and optimized design scheme is also presented here, hoping to provide a valuable reference in the field of microwave-photonic-based sensors. The proposed sensor has potential applications in scenarios requiring high-resolution-curvature measurement.

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