Research and analysis of Brillouin distributed sensing system based on quasi-single-mode few-mode fiber*

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A distributed fiber sensor was fabricated by splicing two single-mode fibers (SMFs) using the few-mode fiber (FMF) technique. A Brillouin optical time domain analysis (BOTDA) system was developed to measure the sensor's temperature and bending performance. Two-mode and four-mode step FMFs were combined to splice the few-mode segment. The results indicate that the temperature response coefficients of the few-mode segment are only slightly higher than those of the connected single-mode segment, measuring at 1.13 MHz/°C and 1.12 MHz/°C, respectively. The minimum bending radius for the sensor is 0.9 cm, and the four-mode bending response curve is superior to that of the two-mode one, proving that 4-SI-FMF offers better bending sensitivity.

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Distributed fiber sensing has garnered significant attention and research interest from scholars due to its numerous advantages, including excellent anti-electromagnetic interference, long measurement distance, high accuracy, and strong reliability[1]. Traditional distributed optical fiber sensing (DOFS) uses single-mode fiber (SMF) as the transmission medium. It uses the light scattering effect caused by the optical signal transmission in the fiber to detect the external environment along the fiber with high sensitivity in real time[2,3]. Among several distributed fiber sensing technologies, Brillouin scattering-based DOFS stands out by offering ultra-high sensitivity and ultra-long-range distributed measurements of temperature and strain. It surpasses others in terms of measurement accuracy and spatial resolution[4], making it a preferred choice for large-scale structural health monitoring in recent years[5-7]. Among them, the Brillouin optical time domain analysis (BOTDA) sensing system based on stimulated Brillouin scattering (SBS) has the advantages of high signal intensity, high measurement accuracy, and wide dynamic range[8-10].

With the rapid growth of the current communication capacity, the conventional SMF communication capacity is gradually approaching the Shannon limit. To surpass the capacity limitations of SMF communication, researchers have turned their attention to mode division multiplexing (MDM) technology[11]. Initially, people tried to use multi-mode fiber (MMF) as the medium of MDM[12]. However, the presence of numerous modes in MMF resulted in inter-mode interference and crosstalk, leading to unsatisfactory performance. As a special MMF, a few-mode fiber (FMF) can transmit several specific modes in its core. Each mode has relatively independent channels, and the spatial transmission modes are orthogonal[13,14]. Compared to MMF, FMF has minor intermodal interference and more accessible mode selection. Furthermore, FMF boasts a larger mode-field area and higher tolerance to nonlinearity when compared to SMFs, making it particularly advantageous for distributed measurements.

When the optical signal is transmitted in the FMF, the Brillouin effect induced by different light modes is different. Without mode separation, the Brillouin mixture spectrum's spectral width is wider than the standard SMF's natural gain of 3 dB (35 MHz)[15]. Currently, using photon lanterns as reuse reconciliation multiplexer is one of the methods of separation of FMF mode. However, this approach comes with certain challenges, including high costs[16,17], susceptibility to damage, lack of

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generality, and substantial insertion loss for small signal strength back Brillouin scattering signals. All of these become FMF complex problems in practical application. In this study, we propose a novel approach where a segment of FMF is integrated between two SMFs. The SMFs at both ends of the FMF are used to excite the fundamental mode in the FMF. At the same time, the FMF in the middle segment can be placed in a quasi-single-mode state, which is used as a sensing fiber to build a loss-type external microwave modulation BOTDA system. A low-cost, highly sensitive distributed sensor was developed and its temperature and bending properties were measured and evaluated.

Similar to the SMF, the FMF, as the transmission medium of an optical waveguide, also produces Brillouin scattering effects during transmission. According to the different incident light intensity and action mechanisms, Brillouin scattering can be divided into spontaneous Brillouin scattering (SPBS) and SBS[13]. When the incident pump power is low, the continuous thermal motion of acoustic phonons in the fiber causes the refractive index of the fiber core to change periodically, resulting in the SPBS of the incident photon. However, when the pump light power into the fiber exceeds the Brillouin threshold, the pump light and Stokes light interact with each other nonlinearly with the help of sound waves. This interaction, known as the electrostriction effect, converts a significant portion of the pump light into Stokes light, thus establishing the SBS effect. In the SMF, the SBS occurs only in the backward direction, that is θ=π. As a particular type of MMF, the FMF can generally transmit 2—10 modes in its fiber core, and each mode requires a different total reflection angle for transmission in the fiber[14]. Its SBS in the fiber can be represented by Fig.1, and its Brillouin frequency shift (*BFS*) can be represented by[14-18]

$$\nu_{\mathrm{B,SI\text{-}FMF}} = \frac{2n_{ij}V_{\mathrm{A}}}{\lambda_{\mathrm{p}}}\cos(\theta_{ij}/2), \tag{1}$$

where V_{A} is the speed of sound, λ_{p} is the center wavelength, n_{ij} and θ_{ij} are the effective refractive index and scattering angle of LP_{ij} mode in FMF, respectively.

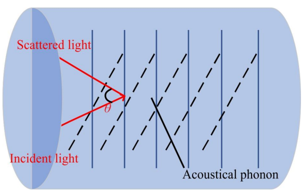

Fig.1 Schematic representation of SBS scattering in FMF

Since there are many modes in the FMF, each with a different scattering angle, and each mode is coupled to each other during transmission, the FMF Brillouin scattering spectrum obtained at the receiver is a mode mixture spectrum, as shown in Fig.2. As can be seen from Fig.2, the 3 dB spectral width of the FMF is wider than that of the SMF. Too wide Brillouin spectral width is very unfavorable for systematic measurements. In this study, we have designed a sensor that effectively reduces the Brillouin spectral width of the FMF, thereby enhancing the measurement performance of distributed systems based on FMF.

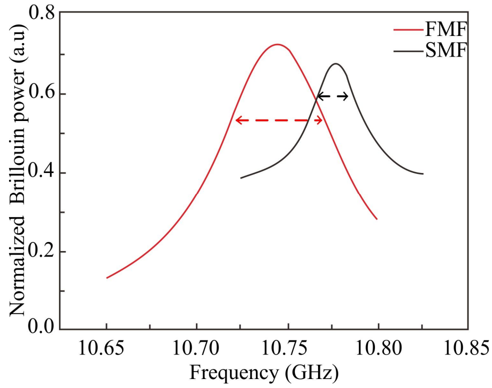

Fig.2 Brillouin gain spectra of MMF and SMF

Based on Brillouin scattering, the changes in Brillouin intensity (BI) under different temperatures and strains are mainly analyzed in the temperature and strain sensing system. When the ambient temperature or stress of the fiber is changed, the thermal expansion effect and elastic optical effect of the fiber will make the material density ρ, refractive index n, Young's modulus E, Poisson's ratio κ, and other parameters change accordingly, and the change of these physical quantities will cause the change of *BFS* in the fiber[19]. The FMF as a function of temperature and strain is[20]

$$\Delta\nu_{\mathrm{B,SI\text{-}FMF}} = C_{\nu T}\Delta T + C_{\nu\varepsilon}\Delta\varepsilon, \tag{2}$$

where $C_{\nu T}$ is the temperature coefficient, $C_{\nu\varepsilon}$ is the strain coefficient, and $\Delta\nu_{\mathrm{B,SI\text{-}FMF}}$ is the change of *BFS* of the SI-FMF. According to Eq.(2), when $\Delta\varepsilon$=0, $\Delta\nu_{\mathrm{B,SI\text{-}FMF}}$ and ΔT are linear. As long as the temperature coefficients are determined, the ambient temperature and temperature variability of the tested fiber can be analyzed and obtained. In the experimental measurements, we strictly adhere to the principle of isolating a single variable, ensuring that the fiber is not affected by stress in the experiment that determines the temperature coefficient. The fiber is always kept at the same temperature without a change in stress experiments.

In this research, a lossy external microwave modulation BOTDA system is constructed, and the system's block diagram is presented in Fig.3. In this experimental system, a highly coherent narrow linewidth laser with a linewidth of 10.3 kHz and a central wavelength of 1 550.060 nm is used as the light source. The light generated by the source is split into upper and lower branches by a 50: 50 polarization-preserving coupler. The upper branch is driven by the pulse signal generated by arbitrary waveform generator (AWG) to perform pulse modulation by the electro-optical modulator

1 (EOM1), and the transmission curve of EOM1 is locked at the valley point by modulator bias controller 1 (MBC1). The modulated pulse signal has a pulse width of 20 ns, a period of 3 μs, and an extinction ratio of 40 dB. The modulated pulse pump light is amplified by the erbium-doped fiber amplifier 1 (EDFA1) and filtered using a grating filter with a center wavelength of 1 550.106 nm and a bandwidth of 0.24 nm, and then passed through the circulator into the sensing fiber. In the lower branch, the electro-optical modulator 2 (EOM2) driven by the microwave signal source (MS) is used to suppress the modulation of the carrier bilateral band, and the modulator bias controller 2 (MBC2) is used to lock the transmission curve of EOM2 at the valley point. The modulated optical signal is amplified by the erbium-doped fiber amplifier 2 (EDFA2), and then the central wavelength is 1 550.232 nm. A grating filter with a bandwidth of 0.238 nm filters out the amplified spontaneous emission (ASE) and upper band signals as a continuous probe light. The continuous probe light enters the other end of the sensing fiber after passing through a polarization scrambler (PS) and isolator (ISO) at a spoiler frequency of 700 kHz, which is used to protect the system components from pump light. The detection light carrying the information along the fiber is output from the 3-port of the optical circulator 3 (OC3). Then it enters the tunable filter to filter out other components, and only the Stokes component is retained. Then it is detected by the photoelectric detector (PD) and displayed and collected by the oscilloscope (OSC).

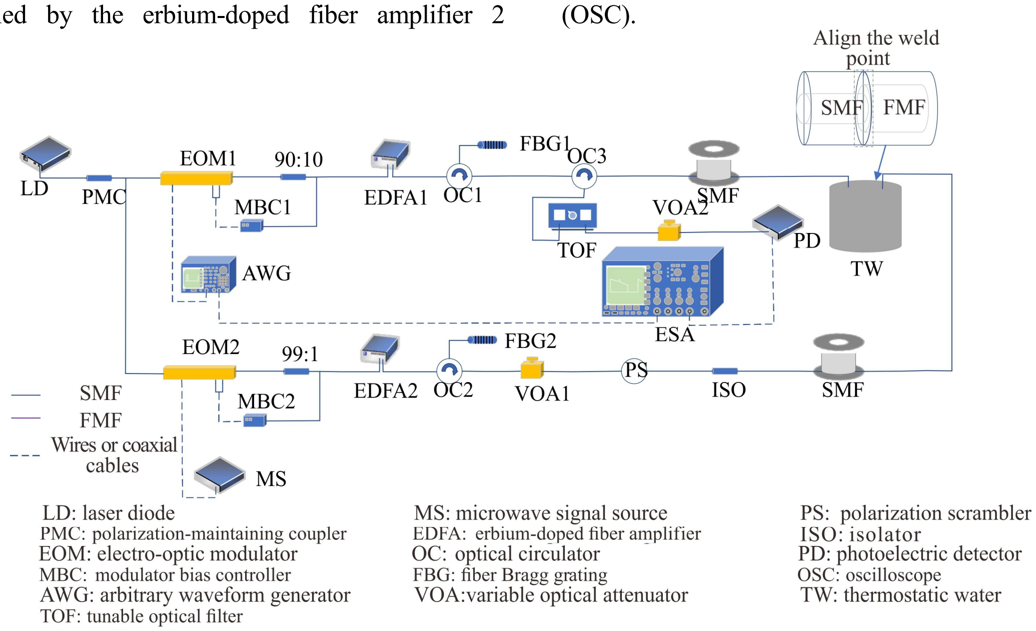

Fig.3 Block diagram of the lossy external microwave modulation BOTDA system

In this study, the two-mode step FMF (SI-2-FMF) and four-mode step FMF (SI-4-FMF) from YOFC Company are used, and the fiber core diameters are 14 μm and 18.5 μm, respectively. Two splintered sensing fibers were fabricated for our experiments. In the first configuration, a 10-m-long two-mode step fiber was fused between a 113-m-long SMF and a 109.4-m-long SMF. Similarly, in the second configuration, a 10-m-long four-mode step fiber was fused between a 101-m-long SMF and a 104-m-long SMF. To avoid experimental contingencies, we performed three sets of repeated experiments, and each data point was collected using an OSC after averaging over 10 000 runs. The results from all three sets of experiments exhibited a high degree of similarity.

For comparative analysis with the SMF, the spliced FMF and its closely connected 10-m-long SMF, totaling 20 m, were used as heating segments, and the temperature measurements of the SMF and FMF segments were processed simultaneously. The ambient temperature was maintained at 27 °C, stepping by 10 °C and the temperature ranges from 30 °C to 70 °C. In each experiment, we measured five sets of temperature data along with one set of room temperature data. The three sets of repeated data were again averaged in the final treatment to obtain the following experimental results. Through Lorentz fitting of the room temperature data, the *BFS* of the SMF at room temperature is 10.65 GHz, while the SI-2-FMF and SI-4-FMF exhibit *BFS* of 10.81 GHz and 10.71 GHz, respectively. The corresponding spectral widths are measured to be 54.0 MHz and 55.8 MHz, which are smaller than the 105 MHz Brillouin gain linewidth observed in MMF. The normalized Brillouin gain spectra (BGS) of two-mode step spliced fiber and four-mode step spliced fiber at 60 °C are shown in Fig.4.

In the experiment, the pulse period was set as 3 μs, the pulse width was set as 20 ns, and the corresponding spatial resolution was 2 m, as shown in Fig.5(a). The data from the heating section of the sensing fiber were extracted for fitting processing, and the fitting result is shown in Fig.5(b). The fitted curves exhibit a linear relationship between temperature and *BFS*, consistent with previous studies. The temperature coefficients of two-mode step split-fiber and four-mode step split-fiber are 1.13 MHz/°C and 1.12 MHz/°C, respectively.

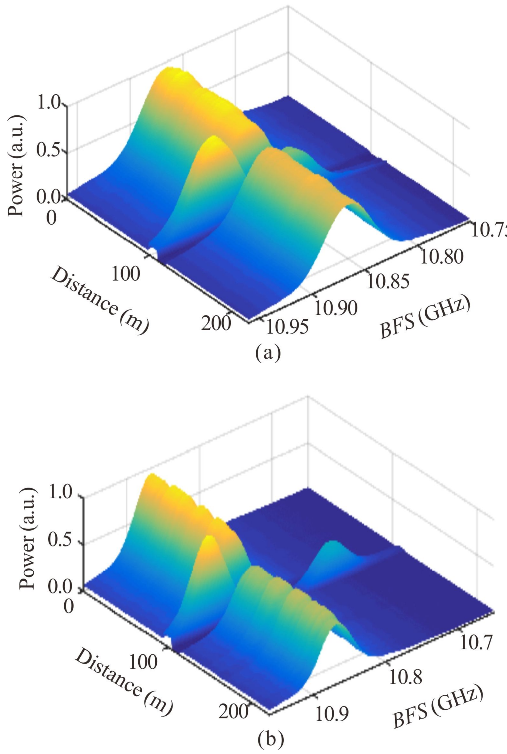

Fig.4 Normalized BGS at 60 °C for (a) SI-2-FMF and (b) SI-4-FMF

The bending resistance of conventional SMFs is feeble. When the bending diameter is small, the optical signal intensity transmitted in the fiber will decrease rapidly, which leads to the reduction of the data intensity after the bending point of the fiber and even the loss of information when the fiber is subjected to the bending stress of small diameter[21,22]. Ensuring that the ambient temperature of the fiber to be measured remained unchanged at 27 °C, we took the middle 3.5 m of the FMF part of the spliced fiber as a bending sensor and wound it on cylinders with diameters of 14.3 cm, 8.2 cm, 4.5 cm, 2.25 cm, 1.5 cm and 0.9 cm for bending measurement. The data for the bending profile was taken out to fitting analysis, yielding the curves presented in Fig.6.

The $\Delta v_{B,SI\text{-}FMF}$ of two fibers have a nonlinear inverse dependence on the bending diameter, which is consistent with previous findings[21]. Additionally, the SI-4-FMF has a higher sensitivity to bending because the core diameter is larger and the mode field area is larger, so it is more suitable for strain measurements with small bending diameters.

Taking SI-4-FMF as an example, we compare the normalized Brillouin power for the case without bending and the case with a 9 mm bending diameter at a scanning frequency of 10.790 GHz, as shown in Fig.7.

The trend of the two curves is the same, there is no change in the power value of the bending segment, and there is almost no loss in the power value of the SMF segment before and after the bending point. Therefore, it can be determined that the bending of the FMF segment doesn't affect the signal strength of the entire fiber segment.

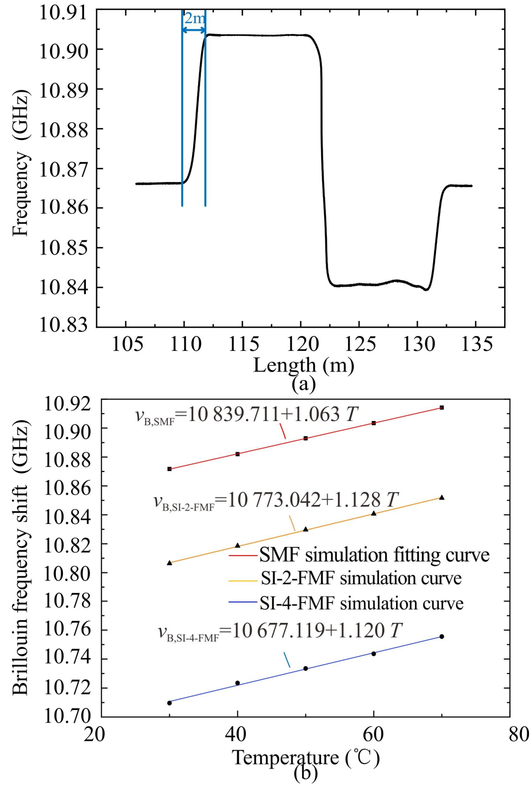

Fig.5 (a) *BFS* at 70 °C; (b) Temperature coefficient fitting curves

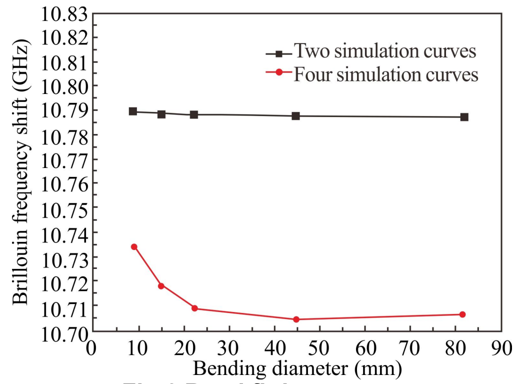

Fig.6 Bend fitting curves

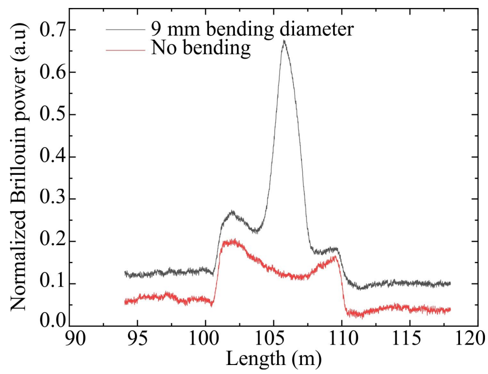

Fig.7 Normalized Brillouin power at 10.69 GHz

In this study, a single FMF is fused to the middle of two SMFs to form a distributed sensor that is easy to implement and low-cost. The sensor served as the sensing fiber in a self-built lossy BOTDA system for conducting comparative experiments on temperature and bending. The theoretical analysis and experimental results show that the 3 dB Brillouin spectral width of the FMF portion of the sensing fiber is slightly narrower than that of the conventional FMF. Within the temperature range from 30 ℃ to 70 ℃, the temperature coefficients of SI-2-FMF and SI-4-FMF were determined to be 1.13 MHz/℃ and 1.12 MHz/℃, respectively, which are not lower than the single-mode temperature response coefficients. The minimum bending diameter achieved by the bending experiments in this paper is 9 mm, which is much better than the SMF. Experimentally, the bending response coefficients of SI-2-FMF and SI-4-FMF are compared, showing a nonlinear inverse relationship with $\Delta v_{\mathrm{B,SI\text{-}FMF}}$. Since the SI-4-FMF has a larger area of the mode field, the bending response is more pronounced and is better suited for measurements at small bending radii. The results presented in this paper can provide a theoretical foundation and experimental basis for future investigations on temperature and bending cross-sensitivity.

Ethics declarations

Conflicts of interest

The authors declare no conflict of interest.

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