

High-Temperature Vector Accelerometer Based on Eccentric Fiber Bragg Grating

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Abstract: Addressing the urgent need for high-temperature vector vibration monitoring in extreme environments such as aerospace and oil exploration, this paper proposes and develops a novel accelerometer based on femtosecond laser-engraved eccentric fiber Bragg gratings (FBGs) and nickel-coated reflectors. This sensor employs a highly localized FBG with a 10 mm length and 1 μ m eccentricity fabricated within a single-mode fiber. It utilizes asymmetric refractive index modulation to achieve direction-sensitive cladding mode coupling. Simultaneously, a 30-nm-thick nickel film is sputter-deposited onto the fiber end-face to form a single-ended reflection structure. This design eliminates complex processes like fiber taper drawing and eccentric fusion splicing, overcoming the stability limitations of existing vector sensors at elevated temperatures. Experimental results demonstrate spectral stability across the 25 °C–1 020 °C temperature range and effective vibration measurement at 800 °C. At the room temperature and 800 °C, the acceleration sensitivities are 0.169 V/g ($R^2=0.993$) and 0.074 3 V/g ($R^2=0.989$), respectively, with a common frequency response range of 15 Hz–25 Hz. The maximum angular response sensitivities are 2.4 V/g and 1.2 V/g, respectively, fully validating its reliable vector detection capability across a wide temperature range. This study provides a compact, mechanically robust, and high-temperature-resistant solution for vibration monitoring in extreme environments.

Keywords: Fiber-optic vector accelerometer; femtosecond laser inscription; eccentric fiber grating; magnetron sputtering; high-temperature sensing; vibration monitoring

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1. Introduction

Accelerometers serve as critical sensing components in fields such as inertial navigation, oil/gas exploration, and structural health monitoring. Maintaining long-term stability and measurement reliability under extreme conditions like high temperatures and pressures is paramount [1–4]. For instance, real-time monitoring of engine vibrations is essential for flight safety in aerospace applications [5]. In deep well drilling, precise measurement of wellbore attitude and pipeline vibrations under high-temperature and high-pressure conditions directly impacts extraction efficiency and operational safety [6]. However, the widely used capacitive and piezoresistive accelerometers not only have limited the measurement accuracy and susceptibility to electromagnetic interference but also exhibit significant performance degradation under high-temperature conditions. In contrast, fiber-optic accelerometers, with their inherent electromagnetic interference immunity, compact structure, high-temperature resistance, and suitability for remote sensing, emerged as an ideal technical solution for vibration monitoring in harsh environments [7–9].

The development of fiber-optic accelerometers has progressed from scalar measurement to vector sensing. Early sensors, such as those based on Michelson interferometers (MI) [10], Fabry-Perot interferometers (FPI) [11], fiber Bragg grating (FBG) diaphragms [12], and distributed Bragg reflector (DBR) fiber lasers [13], were limited to scalar measurement; their responses were independent of the vibration direction, allowing only the single-axis detection. To capture complete vector information, researchers developed novel sensors capable of simultaneously sensing the vibration amplitude and direction. Among these, designs based on multi-axis FBGs and techniques for inscribing FBGs onto polarization-maintaining fibers and multi-core fibers have been successively proposed [14–17]. For

instance, Shenzhen University reported a vector accelerometer based on a multi-core fiber Bragg grating (MCF-FBG), achieving directional vibration measurement up to 550 °C [18]. However, such vector sensors based on specialty fibers rely on complex packaging processes, expensive specialty fiber splicing equipment, and cumbersome grating fabrication procedures. Furthermore, their signal demodulation typically requires precisely controlled fiber lasers, limiting their practical engineering adoption and application.

Consequently, researchers have explored alternative approaches to disrupting cylindrical symmetry within standard single-mode fibers. Tilted fiber Bragg gratings (TFBG), with their asymmetric grating structures, break the fiber's cylindrical symmetry, offering a novel approach for vector vibration sensing. Luo *et al.* [19] developed a vector accelerometer based on an excessively tilted TFBG, enabling simultaneous measurement of amplitude and direction. However, this approach requires simultaneous monitoring of energy changes in the two mutually orthogonal polarization states of the cladding mode at both ends of the fiber, severely limiting its applicability in confined spaces. To overcome this limitation, Guo *et al.* [20] introduced a tapered double-cone structure combined with the TFBG to achieve single-ended reflective measurement. Unfortunately, the conical structure itself introduced issues such as high insertion loss, poor mechanical robustness, and low fabrication reproducibility. Chen *et al.* [21] employed femtosecond laser point-by-point etching assisted by slit beam shaping to engrave asymmetric elliptical gratings within the core of the single-mode fiber. By depositing gold films onto the fiber end-face, they fabricated a single-ended reflective sensor requiring no structural modification of the fiber. This approach maintained mechanical integrity while extending the operating temperature to 450 °C. However, when temperatures exceed 500 °C, the gold film softens, agglomerates, and peels off,

causing its optical performance to deteriorate sharply. This makes it difficult to meet the practical requirements of ultra-high-temperature scenarios such as aerospace engine monitoring and deep well exploration.

To address the technical bottleneck of insufficient thermal stability in existing fiber-optic vector accelerometers under ultra-high temperature conditions, this paper proposes a novel vector accelerometer designed for extreme high-temperature environments. Its core innovations include: 1) employing femtosecond laser inscription to create highly localized eccentric FBGs within the single-mode optical fiber, leveraging their asymmetric refractive index modulation to achieve direction-sensitive cladding mode coupling without requiring specialty fibers or complex assemblies; 2) a single-ended reflective intensity demodulation scheme is employed, enabling vector calculation by monitoring a single cladding mode intensity, resulting in a simple and low-cost system;

3) innovatively employing a high-melting-point (approximately 1455 °C) nickel film as the end-face reflector, thereby addressing the failure of reflective layers in ultra-high-temperature environments at the material level. This paper systematically characterizes the developed sensor's acceleration sensitivity, spectral response, and directional dependency under temperatures up to 800 °C. Experimental results demonstrate that the sensor maintains excellent spectral stability under extremely high-temperature conditions while delivering reliable vector detection performance and long-term operational reliability.

2. Sensor design and fabrication

Figure 1 shows the schematic structure of the proposed high-temperature vector accelerometer probe. The core sensing unit consists of a highly localized FBG inscribed by a femtosecond laser and a 30-nm-thick nickel film reflector deposited on the fiber end-face.

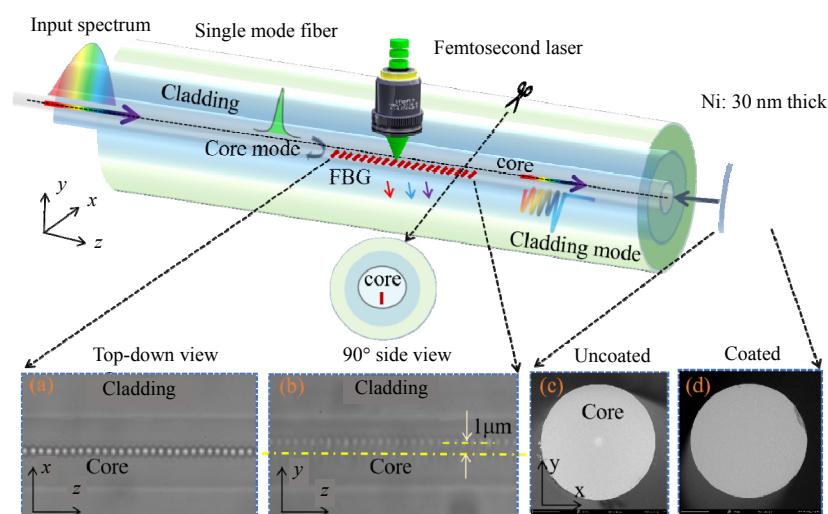


Fig. 1 Schematic of a highly localized eccentric FBG fiber accelerometer probe: (a) top view, (b) side view (showing grating eccentricity), (c) fiber end face before coating, and (d) fiber end face after coating.

The FBG is fabricated using the femtosecond laser point-by-point writing technology. The core of the writing system is a frequency-doubled regenerative amplified femtosecond laser (Pharos, Light Conversion, Lithuania), with a central laser wavelength of 514 nm, a pulse width of 290 fs, and

a repetition rate of 200 kHz. In the experiment, the single-mode fiber with its cladding removed is mounted on a three-dimensional air-bearing displacement stage (Aerotech ABL15010, ANT130LZS, and ANT130V-5, USA) to achieve nanometer-level displacement control, and the laser

pulse is focused onto the fiber core via an oil-immersion objective (Leica, 100×/1.25 NA, Germany). Under optimized process parameters (laser pulse energy 50 nJ and platform movement speed 0.1 mm/s), an FBG with a grating period of 1.072 μm , the total length of 10 mm, and approximately 1 μm eccentricity is successfully fabricated. As shown in Figs. 1(a) and 1(b), this eccentric structure induces an asymmetric distribution of the refractive index modulation (RIM) region within the core, thereby breaking the inherent cylindrical symmetry of the fiber. The sensing mechanism lies in the following: when the fiber bends due to vibration, the relative azimuth angle between the bending direction and the asymmetry axis of the grating directly modulates the coupling efficiency between the core and cladding modes. This provides the physical basis for identifying the vibration direction [22, 23].

To achieve high-efficiency single-ended reflective measurement, this study employs magnetron sputtering to deposit a 30-nm-thick nickel film on the cut end face of the FBG. Nickel is selected as the reflective layer primarily due to its excellent overall stability within the target high-temperature range (25 $^{\circ}\text{C}$ –1 020 $^{\circ}\text{C}$). On one hand, nickel forms a dense and stable NiO passivation layer in oxygen-rich high-temperature environments, effectively suppressing ongoing film oxidation and ensuring long-term optical performance [24]. On the other hand, despite differences in thermal expansion coefficients between the nickel and quartz fiber, the resulting interfacial compressive stress during post-high-temperature cooling actually enhances film-substrate bonding strength, improving mechanical reliability under thermal cycling [25]. These combined chemical and mechanical stabilities form the foundation for nickel-film reflectors to maintain optical integrity under extreme temperatures, such as 800 $^{\circ}\text{C}$.

The fiber end-face morphology before and after

coating is shown in Figs. 1(c) and 1(d), respectively. The nickel coating serves a dual critical function in this sensor design. First, as a broadband high-reflectivity mirror (reflectivity > 90% at 1 550 nm), it transforms the sensing structure from transmissive to single-ended reflective. This allows the light source and detector to be positioned at the same end of the fiber, significantly simplifying the system architecture and enhancing deployment flexibility in confined spaces. More fundamentally, this reflective coating enhances the FBG's modulation effect on the light field through a “double-pass reflection” mechanism, effectively recovering cladding mode energy that would otherwise be lost. This significantly amplifies the vibration-sensitive cladding mode resonance signal – which is difficult to detect due to losses in single-pass transmission – within the reflected spectrum [comparing Figs. 2(a) and 2(b)], thereby achieving a fundamental improvement in the signal-to-noise ratio (SNR). This mechanism effectively extracts and amplifies the inherently weak and vibration-sensitive cladding mode resonance signal, providing a high-quality signal source for high-sensitivity vector demodulation. Simultaneously, this design eliminates complex post-processing steps found in the traditional approaches, such as fiber taper drawing, eccentric fusion splicing, or core misalignment, while maintaining the fiber's inherent mechanical strength. It simplifies the probe structure and optimizes the measurement process.

To clarify the modulation effect of the nickel-coated reflector on the spectral characteristics of the fiber grating, we systematically characterize the FBG spectral properties before and after the nickel plating. The characterization system comprises a broadband light source (BBS, YSL SC Series, China) and an optical spectrum analyzer (OSA, Yokogawa AQ6370C, Japan).

As shown in Fig. 2(a), without the nickel coating, the FBG transmission spectrum exhibits a

core-mode resonance peak exceeding 20 dB at 1 548.43 nm. Multiple cladding-mode resonances with intensities above 10 dB are present across a broad wavelength range from 1 300 nm to 1 548 nm, indicating significant core-cladding mode coupling efficiency. However, only a weak core mode reflection peak is discernible in its reflection spectrum, while the cladding mode signal is obscured by noise.

After depositing a nickel film on the fiber end-face, the reflection spectrum undergoes significant changes [Fig. 2(b)]: a series of dense resonance peaks are observed in the short-wavelength region (1 300 nm to 1 548 nm). These peaks originate from the coupling between the core fundamental mode (LP_{01}) and forward-propagating cladding modes of different orders (e.g., LP_{0n}). The asymmetric refractive index modulation introduced by the eccentric FBG disrupts the fiber's circular symmetry, enabling this coupling. According to phase-matching conditions, the wavelength $\lambda_{res,m}$ of the m th-order cladding mode resonance peak is determined by the following equation:

$$\lambda_{res,m} = (n_{eff,core} - n_{eff,cladding,m})\Lambda. \quad (1)$$

In the equation, $\lambda_{res,m}$ represents the wavelength of the m th cladding mode resonance peak. $n_{eff,core}$ denotes the effective refractive index of the core fundamental mode. $n_{eff,cladding,m}$ indicates the effective refractive index of the m th-order cladding mode. Λ is the grating period. Since $n_{eff,core} > n_{eff,cladding,m}$, all cladding mode resonant peaks occur at the short-wavelength side of the core mode's main Bragg peak (approximately 1 548.43 nm). The coupling efficiency of these cladding modes exhibits high sensitivity to the direction of fiber bending, making them carriers of information for subsequent vibration vector calculations.

Notably, the intensity of the core mode reflection peak (1 548.43 nm) is significantly enhanced, with its peak-to-peak value increasing to approximately 6 dB. This enhancement renders the previously indistinguishable cladding mode resonances clearly visible in the reflection spectrum. Consequently, simultaneous monitoring of both the core and cladding modes is achieved in a single-ended reflection configuration, laying the foundation for effective demodulation of subsequent vibration sensing mechanisms.

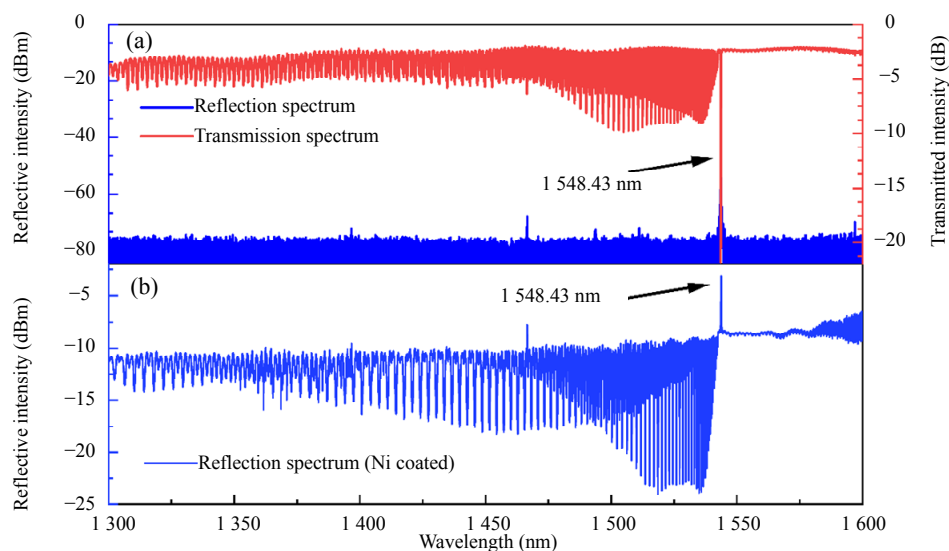


Fig. 2 Spectral characteristics of the highly localized FBG: (a) transmission and reflection spectra before the nickel plating, and (b) reflection spectrum after the nickel plating.

3. Static characterization

To evaluate the static sensing performance of the developed accelerometer, we construct the test system shown in Fig. 3. This system comprises a broadband light source (BBS, YSL SC Series, China), an optical spectrum analyzer (OSA, Yokogawa AQ6370C, Japan), a curvature plate capable of precise bending control, and a fiber-optic rotation fixture. Using this platform, we investigate the sensor's response characteristics to changes in the bending curvature and its dependence on the bending direction. The specific experimental procedure is as follows: first, by adjusting the curvature plate, the sensor is subjected to bending ranging from 0 m^{-1} to 1.1 m^{-1} to analyze its curvature sensitivity. Subsequently, under a fixed curvature of 1.1 m^{-1} , the sensor is rotated around its axis by one full revolution using the rotating fixture, with 60° increments, to evaluate its angular response characteristics. Throughout testing, continuous monitoring of an LP_{0n} cladding mode at 1533.74 nm records changes in its resonance intensity.

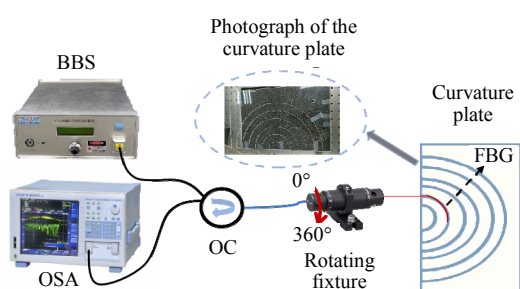


Fig. 3 Schematic diagram of the static measurement system for the localized FBG accelerometer (OC: optical circulator).

3.1 Static curvature response

Figure 4(a) displays the total reflection spectrum across the 1525 nm – 1560 nm wavelength range. To thoroughly analyze the sensor's response characteristics, the LP_{0n} cladding mode at 1533.74 nm and the core mode at 1548.43 nm are examined in detail. As shown in Fig. 4(b), the resonance intensity of the cladding mode exhibits a monotonically and significantly decaying trend as

the bending curvature increases from 0 m^{-1} to 1.1 m^{-1} , with a total change exceeding 10 dB . This phenomenon can be attributed to the strain gradient distribution induced by bending within the optical waveguide, which alters the phase-matching conditions between the core layer and specific cladding modes, ultimately leading to reduced coupling efficiency. In stark contrast, the reflection intensity of the core mode remains highly stable across all tested curvatures, with fluctuations below 1 dB [Fig. 4(c)]. These results indicate that the selected cladding mode exhibits extreme sensitivity to lateral bending, making it suitable as a sensitive signal for vibration sensing. Conversely, the core mode demonstrates insensitivity to bending, enabling it to serve as a stable and built-in reference for effectively compensating for common-mode disturbances such as the temperature and static strain. Furthermore, by simultaneously monitoring the intensities of two distinct cladding modes (e.g., LP_{02} and LP_{03}) and applying differential processing, common-mode noise introduced by environmental perturbations can be further suppressed. This enhances the robustness of intensity-demodulated vibration vector detection systems in practical applications.

3.2 Static angle response

Figure 5(a) displays the total reflection spectra of the sensor at different azimuth angles (1525 nm – 1560 nm). It can be observed that the resonance intensity of the cladding mode exhibits regular periodic modulation with angle variation. Quantitative analysis of the LP_{0n} cladding mode at 1533.74 nm [Fig. 5(b)] reveals an amplitude fluctuation of approximately 10 dB with angular variation, demonstrating significant directional dependence. In contrast, the core mode reflection intensity at 1548.43 nm remains essentially constant across all angles [Fig. 5(c)], further validating its excellent reliability as a reference signal. These

results demonstrate that monitoring the intensity variation of a single cladding mode effectively identifies the vibration direction. The angular response curve exhibits an approximate “8” distribution pattern, closely matching the directional

coupling characteristics introduced by the asymmetric refractive index modulation of the eccentric fiber grating. This experimentally validates the sensor’s feasibility as a vector accelerometer.

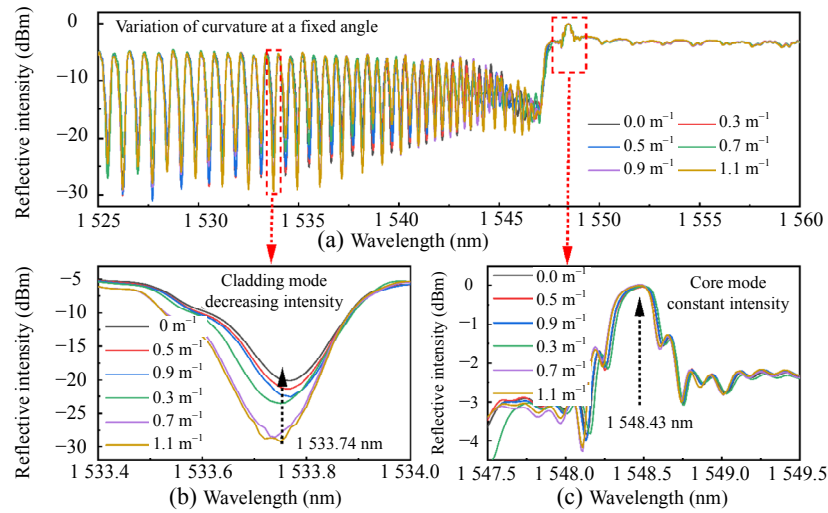


Fig. 4 Spectral responses under different bending curvatures: (a) total reflection spectrum (1525 nm–1560 nm), (b) enlarged view of the cladding mode at 1533.74 nm, and (c) enlarged view of the core mode at 1548.43 nm.

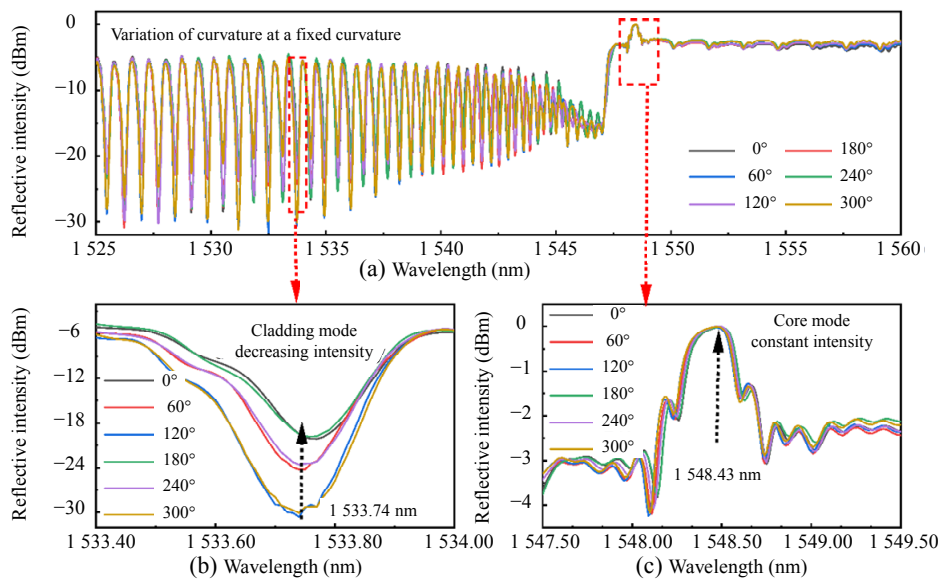


Fig. 5 Spectral responses at different angles: (a) total reflection spectrum (1520 nm–1560 nm), (b) magnified view of the cladding mode at 1533.74 nm, and (c) magnified view of the core mode at 1548.43 nm.

4. Temperature resistance and film stability analysis

To evaluate the spectral stability and functional reliability of the sensor under high-temperature conditions, it is subjected to thermal field testing in

a tube furnace (Carbolite, Gero HTRH, UK). The experiment employs a stepwise heating protocol: first, the temperature is raised from the room temperature to 450 °C at a rate of 5 °C/min, followed by annealing at this temperature for 24 hours to

relieve internal stresses and stabilize the refractive index modulation structure of the grating. Subsequently, heating continues at the same rate to 1 020 °C.

Figures 6(a) and 6(b) show the evolution of the sensor's reflection spectrum in the 1 525 nm–1 560 nm band as a function of the temperature after annealing. Throughout the heating process, the resonant wavelengths of both the core mode and cladding mode shift toward longer wavelengths (“redshift”) with increasing temperatures, exhibiting typical temperature-dependent characteristics dominated by both thermo-optic and thermal expansion effects [26, 27]. Notably, even at 1 020 °C, the spectral line shape remains stable without significant broadening or distortion, indicating that the sensor maintains

excellent structural integrity and optical stability under extreme temperatures.

Further quantification of the sensor's temperature sensitivity is achieved using third-order polynomial fitting, with the fitted curve and experimental data shown in Fig. 6(c). Across three temperature ranges 25 °C–450 °C, 450 °C–800 °C, and 800 °C–1 020 °C, the core mode sensitivities are 12.72 pm/°C, 12.77 pm/°C, and 10.67 pm/°C, respectively, while the cladding mode sensitivities are 12.03 pm/°C, 13.10 pm/°C, and 11.67 pm/°C. The sensitivity changes across each temperature range are gradual, with no significant inflection points or abrupt changes, demonstrating consistent and stable temperature response characteristics across the wide temperature range of 25 °C–1 020 °C.

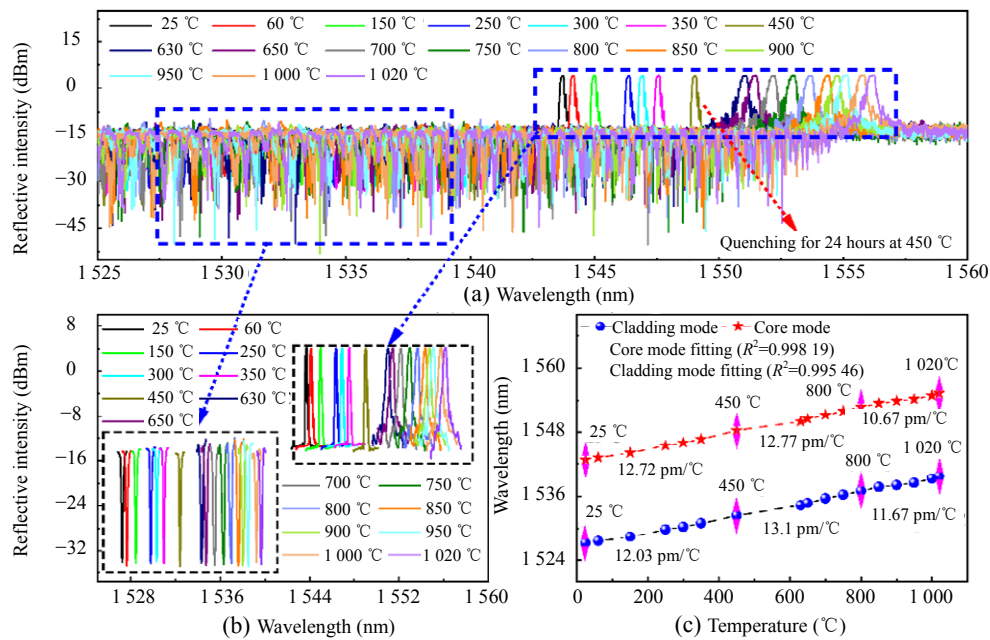


Fig. 6 Spectral and temperature stability of nickel-plated FBGs: (a) spectral response in the 1 525 nm–1 560 nm band versus temperature, (b) evolution of selected cladding mode and core mode reflection spectra, and (c) wavelength-temperature response curves for the cladding mode and core mode.

To evaluate the performance advantages of nickel films under ultra-high temperature conditions, we design a comparative experiment. Nickel (Ni) films and gold (Au) films are placed in the same tube furnace and heated simultaneously to 1 020 °C. We systematically analyze the morphological

evolution and spectral response characteristics of both films at different temperature points (25 °C, 450 °C, and 1 020 °C).

The experimental results are shown in Fig. 7. As the temperature increases, microscopic pore structures gradually form on the nickel film surface,

with pore density rising with the temperature [Figs. 7(a)–7(c)]. Despite these morphological changes, the corresponding FBG reflection spectra maintain excellent spectral stability throughout the heating process, exhibiting only a wavelength redshift consistent with theoretical predictions [Fig. 7(d)]. In stark contrast, the gold film exhibits noticeable surface expansion and wrinkling at 450 °C [Figs. 7(e)–7(g)], followed by severe delamination at 1 020 °C. Correspondingly, its optical performance deteriorates significantly, with the reflection spectrum intensity fluctuating violently and the spectral profile becoming severely distorted [Fig. 7(h)]. This result aligns with the conclusion reported in [21] that gold films degrade above 500 °C. Therefore, although gold (Au) films are commonly used as high-reflectivity coatings in the low-to-medium temperature range (typically ≤ 450 °C) and have been successfully applied in fiber-optic sensors, they undergo rapid

atomic diffusion, agglomeration, and oxidation at temperatures approaching or exceeding 500 °C. This leads to a sharp decline in reflectivity and functional failure. Comparative experiments conclusively demonstrate that nickel films exhibit significantly superior thermal stability and optical reliability to gold films under ultra-high temperatures, making them an ideal reflector material for constructing fiber-optic sensors suitable for extreme ultra-high-temperature environments. It should be noted that the temperature field tests in this study aim to validate the functional reliability of the sensor during a single high-temperature operational cycle. For applications requiring repeated extreme thermal cycling, long-term performance may be affected by factors such as crystallization and embrittlement of the quartz fiber substrate. Further evaluation through dedicated high-low temperature cycling durability tests is warranted, which will be addressed in subsequent research.

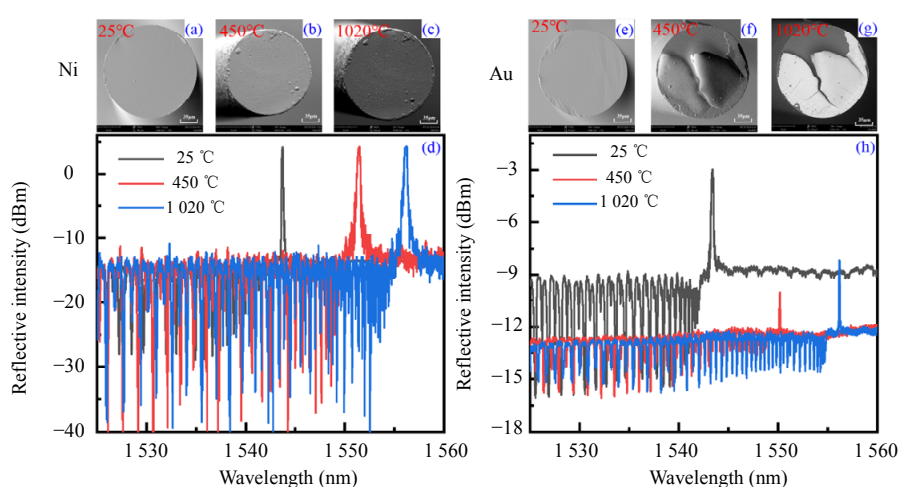


Fig. 7 Temperature characteristics comparison between Ni and Au films: (a)–(c) microscopic images of the Ni film at 25 °C, 450 °C, and 1 020 °C, (d) reflectance spectrum of the Ni film FBG, (e)–(g) microscopic images of the Au film at 25 °C, 450 °C, and 1 020 °C, and (h) reflectance spectrum of the Au film FBG.

5. Dynamic characterization

To evaluate the sensor's dynamic sensing performance, we construct the test system shown in Fig. 8. The core components of this system comprise a tunable laser (Keysight, N7776C, USA), an electromagnetic vibration table (Bruel & Kjaer,

4808, Denmark), an optoelectronic detector (Newport, 2053, USA), an oscilloscope (Tektronix, MDO3054, USA), and an OC. During testing, a commercial standard accelerometer (Bruel & Kjaer, 8305, Denmark) is rigidly mounted on the vibration table surface for real-time calibration and verification of the applied vibration signal. The

sensing probe is fixed to the vibration table exciter via a precision rotary stage (Thorlabs, HFR007, USA) to enable flexible control of the vibration direction. Its sensing mechanism is as follows: a tunable laser outputs a continuous laser precisely matched to the resonant wavelength of a specific cladding mode or a core mode, which is then introduced into the sensor probe via a circulator. Driven by a signal generator and a power amplifier,

the vibration table generates controllable sinusoidal excitation. This dynamic bending directly modulates the mode coupling efficiency between the core and cladding layers of the eccentric FBG, causing corresponding changes in reflected optical power. The reflected light is converted into a voltage signal via a circulator and a photodetector, ultimately acquired by an oscilloscope for subsequent analysis.

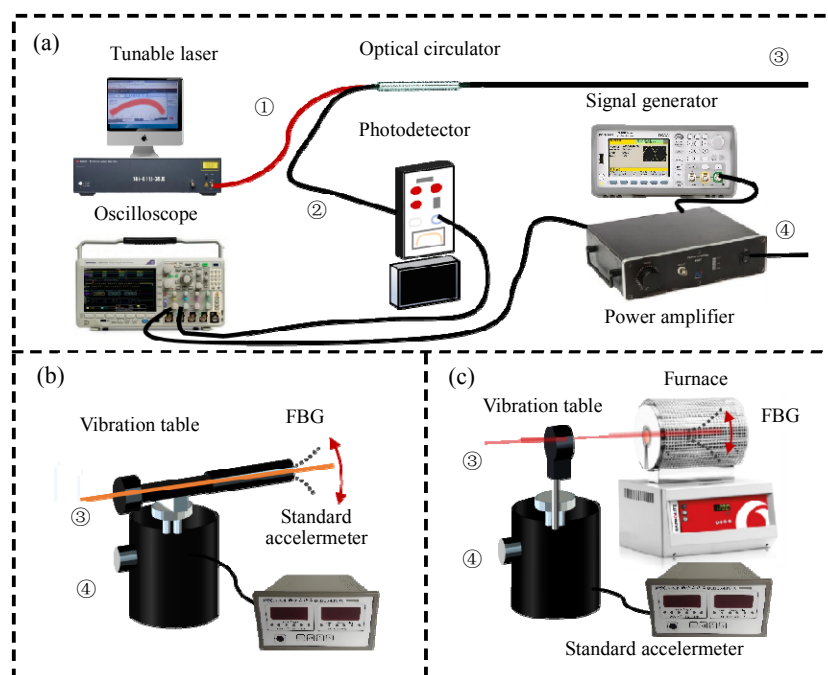


Fig. 8 Schematic of the vibration test system: (a) signal acquisition unit of the test system, (b) room-temperature vibration test system, and (c) high-temperature vibration test system.

5.1 Vibration response characteristics

To characterize the fundamental dynamic response of the sensor, sinusoidal vibration excitation is applied at both the room temperature and 800 °C under a free fiber length of $L=5.5$ cm.

At the room temperature, the sensor exhibits a clear dynamic response to excitation at a frequency of 22.5 Hz and an acceleration of 2.5 g. As shown in Fig. 9(a), the reflected optical power of the cladding mode displays sinusoidal fluctuations consistent with the excitation frequency, while the power output of the core mode maintains a steady straight

line, consistent with the conclusions from the static bending test in Section 3. A fast Fourier transform (FFT) of the cladding mode signal reveals a sharp fundamental peak at 22.5 Hz in its spectrum [Fig. 9(b)], alongside the secondary and tertiary harmonic components observed at 51.5 Hz and 77.3 Hz. These harmonics primarily originate from the nonlinear response of the sensor within its cantilever beam structure.

To accurately evaluate the sensor's dynamic response under the high-temperature environment of 800 °C, the detection wavelength must be locked at the optimal operating point of the cladding mode resonance peak. For this purpose, an active

wavelength tracking method is employed: first, a complete reflection spectrum is acquired at 800 °C under steady-state conditions to determine the new central wavelength of the cladding mode resonance peak after temperature drift. Subsequently, the tunable laser output wavelength is locked at the point of the maximum slope within the linear region of this resonance peak for vibration testing. The sensor maintains stable dynamic response characteristics [Figs. 9(c) and 9(d)], with its resonance frequency sustained at 22.5 Hz, indicating consistent kinetic properties under high-temperature

conditions. Notably, the cladding mode exhibits a well-preserved sinusoidal response even under extreme temperatures, while the core mode power remains stable. Compared to room-temperature results, higher-order harmonic components in the spectrum are suppressed at elevated temperatures. This suggests that high-temperature annealing may have improved the damping properties of the fiber material or promoted structural homogenization. Consequently, while maintaining a stable resonance frequency, the linearity of the dynamic response is optimized.

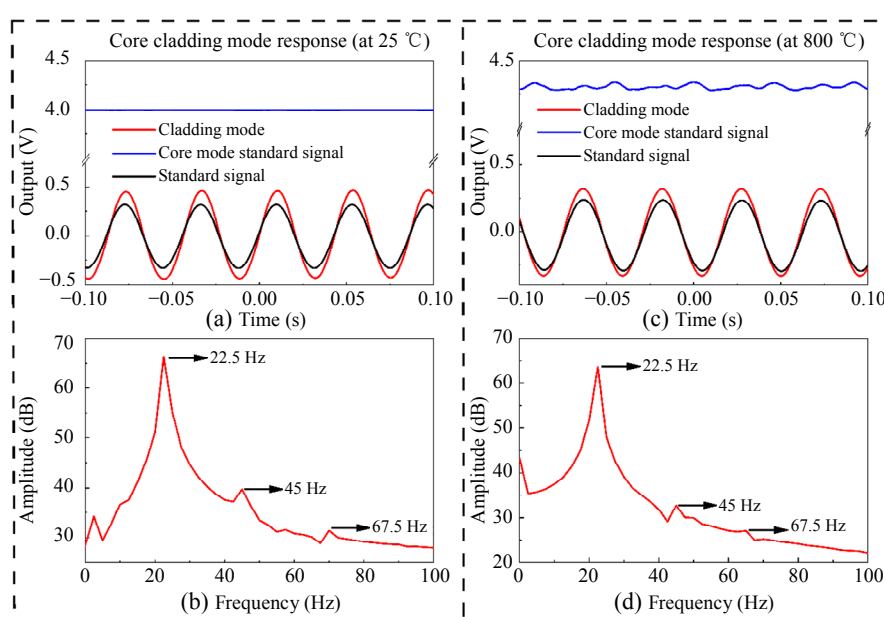


Fig. 9 Dynamic response analysis of the accelerometer: (a) power output of the cladding mode and core mode at the room temperature (25 °C), (b) spectral analysis of the cladding mode at the room temperature (25 °C), (c) power output of the cladding mode and core mode at the high temperature (800 °C), and (d) spectral analysis of the cladding mode at the high temperature (800 °C).

5.2 Linear acceleration response

To quantitatively evaluate the linearity and sensitivity of the sensor at different temperatures, tests are conducted at the room temperature (25 °C) and high temperature (800 °C) with a fixed free fiber length of $L=5.5$ cm. All applied vibration accelerations are calibrated in real time using a commercially available standard accelerometer (Bruel & Kjaer, 8305, Denmark) installed in parallel to ensure measurement accuracy.

At the room temperature, the sensor is subjected to sinusoidal vibrations with a frequency of 22.5 Hz

(its room-temperature resonance frequency) and acceleration amplitudes ranging from 0.6 g to 5 g. As shown in Fig. 10(a), the voltage signal output from the cladding mode exhibits a regular sinusoidal waveform highly synchronized with the excitation signal, indicating excellent dynamic tracking capability with a detection lower limit of 0.6 g. Figure 10(b) further illustrates the relationship between the output voltage amplitude and the applied acceleration. The acceleration sensitivity obtained through linear fitting is 0.169 V/g, exhibiting excellent linearity ($R^2=0.993$).

The linearity test is subsequently repeated at 800 °C. Due to a change in the sensor mounting method, the excitation frequency is adjusted to 32 Hz (the sensor's resonance frequency at the high temperatures), with the acceleration test range set to 0.5 g–5 g. As shown in Fig. 10(c), the sensor still outputs stable and clear sinusoidal response signals at high temperatures, with an acceleration detection lower limit of 0.54 g, confirming its effective vibration sensing capability in high-temperature environments. The linear fitting results [Fig. 10(d)] indicate the sensitivity of 0.074 3 V/g at high temperatures ($R^2=0.989$). Compared to the room-temperature sensitivity, the high-temperature sensitivity decreases by approximately 56%. This difference primarily stems from the rigid encapsulation method adopted during high-temperature testing to adapt to the tube furnace environment. This method significantly alters the sensor's mechanical boundary conditions, leading to an increase in overall equivalent stiffness. According

to the cantilever beam model, the increased system stiffness (k) reduces the bending deformation of the fiber under identical inertial forces, diminishing the optical modulation response and directly manifesting as the decreased voltage sensitivity. Simultaneously, it elevates the resonance frequency, consistent with the experimentally observed shift from 22.5 Hz to 32 Hz. Although a decrease in Young's modulus of the quartz fiber with rising temperatures reduces stiffness to some extent, under the experimental conditions, the stiffness enhancement effect introduced by encapsulation completely dominates the weak counteracting effect of material softening. Therefore, the net effect remains an increase in stiffness and a decrease in sensitivity. Additionally, high-temperature encapsulation may introduce minor uncalibrated directional deviations, which is another potential factor contributing to the sensitivity being slightly lower than that theoretically expected.

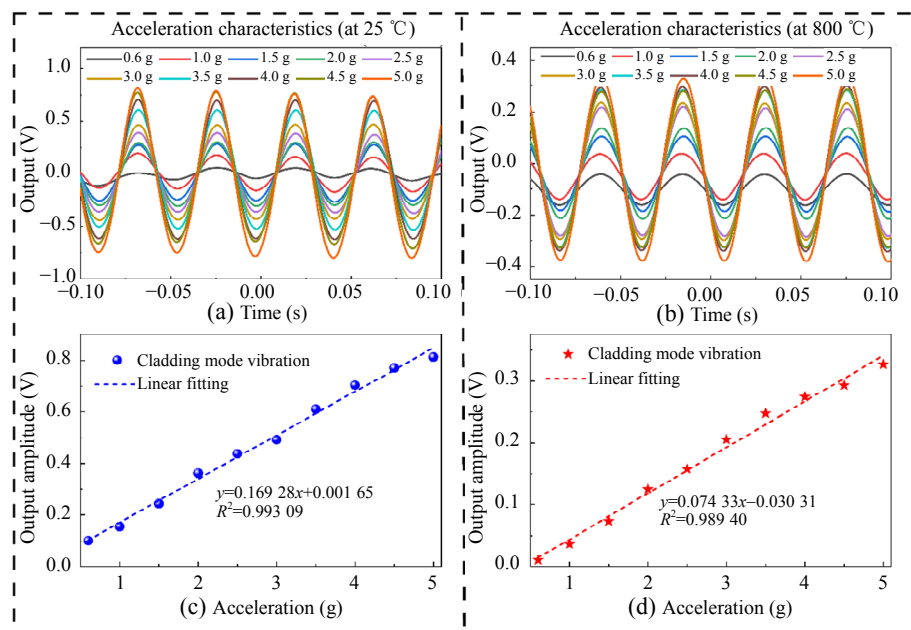


Fig. 10 Acceleration response characteristics of the sensor: (a) time-domain curve of the cladding mode output voltage at the room temperature, (b) linear relationship between the output voltage amplitude and acceleration at the room temperature, (c) time-domain curve of the cladding mode output voltage at the high temperature, and (d) linear relationship between the output voltage amplitude and acceleration at the high temperature.

5.3 Frequency response

To evaluate the sensor's dynamic operating

systematically characterized at both the room temperature (25 °C) and high temperature (800 °C).

The sensor's sensing element can be modeled as a uniformly distributed cantilever beam with one end fixed and the other free. Its dynamic behavior is described by a distributed parameter system, primarily dominated by a first-order bending mode. When the excitation frequency is far below higher-order modes, the system can be equivalently modeled as a lumped parameter second-order mass-spring-damper system. The transfer function from the ground acceleration $A(\omega)$ to sensor output voltage $V_{\text{out}}(\omega)$ is expressed as

$$H(\omega) = \frac{V_{\text{out}}(\omega)}{A(\omega)} = \frac{S_0}{\omega_n^2 - \omega^2 + 2j\zeta\omega_n\omega} \quad (2)$$

where S_0 is the system's low-frequency sensitivity (V/g), $\omega_n = 2\pi f_n$, and ζ is the system's equivalent damping ratio, primarily determined by the fiber material loss and boundary damping. The theoretical value of the first-order natural frequency f_n can be derived from the cantilever beam model [28, 29]:

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m_{\text{eff}}}} = \frac{1}{2\pi} \sqrt{\frac{8EI}{\rho AL^4}} \quad (3)$$

where E is the Young's modulus of the fiber, I is the moment of inertia of the fiber cross-section (for a circular cross-section, $I = \pi r^4/4$), ρ is the fiber density, A is the fiber cross-sectional area ($A = \pi r^2$), and L is the free fiber length. This model indicates that the sensor's resonance frequency primarily depends on the free fiber length L and the material property E . Theoretically, the resonance frequency is proportional to L^{-2} , enabling precise resonance frequency tuning through L design.

At the room temperature, the sensor ($L = 6.0$ cm) is subjected to a vibration excitation of 3 g acceleration. A frequency sweep test is conducted within the range of 10 Hz–30 Hz with a step size of 2 Hz. As shown in Fig. 11(a), the reflected light intensity exhibits a peak at 19 Hz, demonstrating typical resonance characteristics. The corresponding normalized amplitude-frequency response curve [Fig. 11(b)] indicates that the sensor possesses an effective flat response bandwidth within the 15 Hz–25 Hz frequency range.

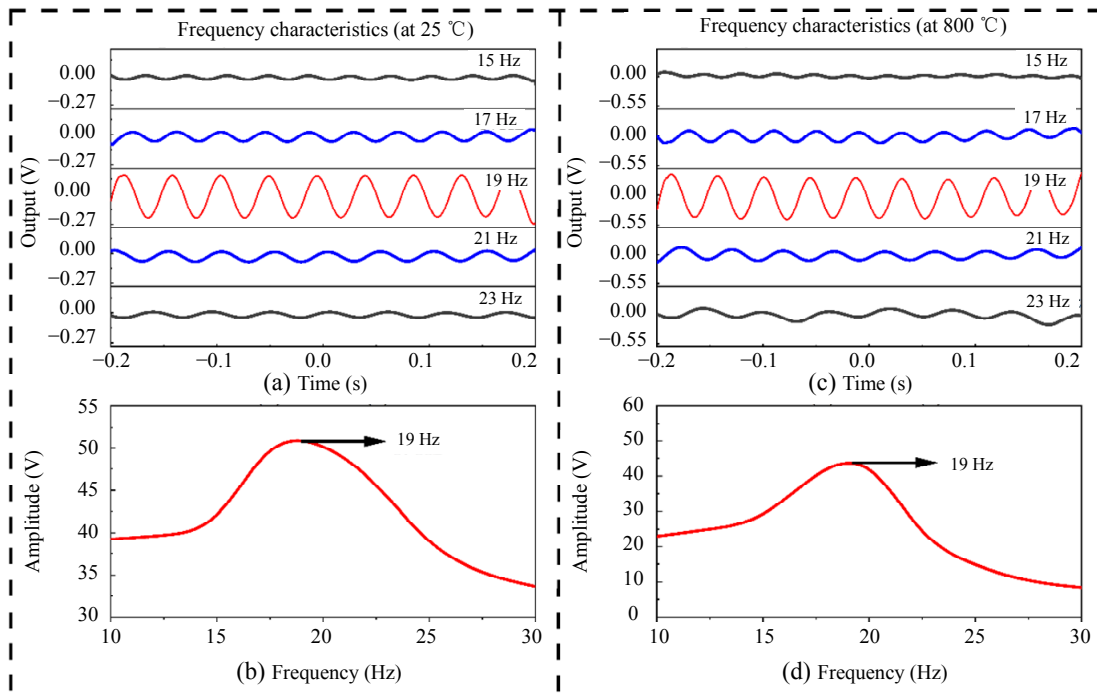


Fig. 11 Frequency response characteristics at different temperatures: (a) vibration versus frequency at the room temperature (the resonance frequency 26 Hz), (b) amplitude-frequency response curve at the room temperature, (c) vibration versus frequency at the high temperature (the resonance frequency 32 Hz), and (d) amplitude-frequency response curve at the high temperature.

At 800 °C, a sweep test is conducted with an acceleration of 1.64 g across the 10 Hz–30 Hz range. As shown in Figs. 11(c) and 11(d), the sensor's resonance frequency remains stable at 19 Hz, with the effective operating bandwidth shifting to 15 Hz–25 Hz. This demonstrates the sensor's stable dynamic characteristics and excellent temperature consistency under extreme high-temperature conditions.

This study focuses on verifying the sensor's fundamental vector functionality and linear response capability under extreme high temperatures. The experimentally determined flat response bandwidth (15 Hz–25 Hz) provides a clear operational frequency range for practical applications. Within this bandwidth, the sensor's sensitivity frequency response characteristics can be effectively evaluated

through its amplitude-frequency curve, offering reliable performance assurance for vibration measurements within known excitation frequency ranges.

5.4 Angular response

To quantitatively evaluate the sensor's vector detection capability, its directional response characteristics are systematically characterized with a free fiber length of $L=6.0$ cm. Using a rotating fixture, the measurement is taken at 10° increments from 0° to 360°, capturing angular response characteristics at both the room temperature and 800 °C. The results shown in Fig. 12 reveal a typical symmetrical “8” distribution in the sensitivity polar plot, indicating the sensor's excellent vector detection capability.

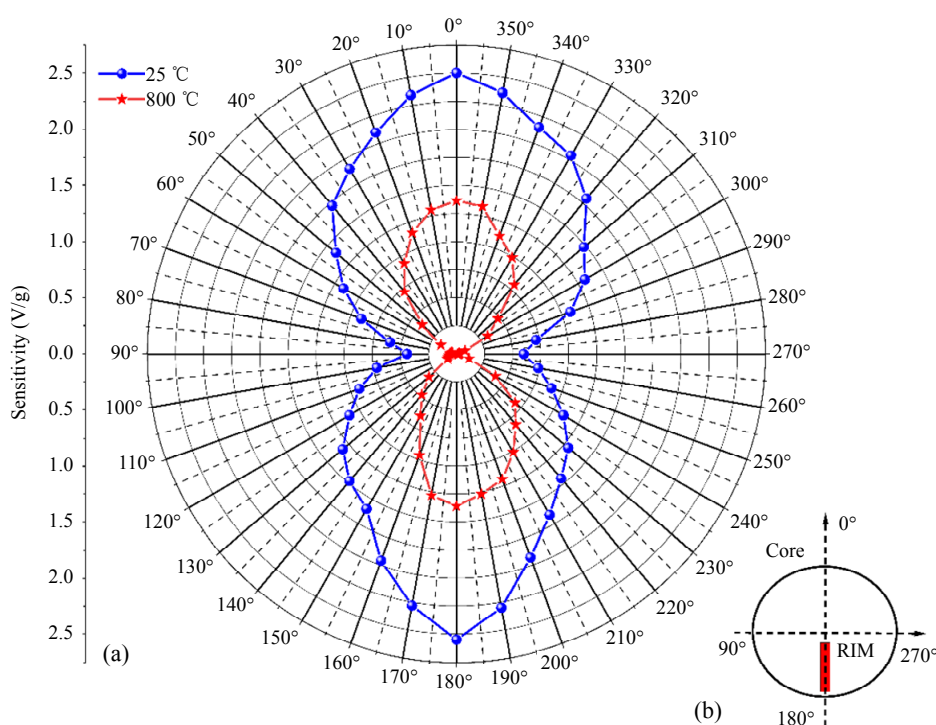


Fig. 12 Directional response characteristics of the accelerometer at the room temperature and elevated temperatures.

At the room temperature (25 °C), the sensor exhibits the maximum sensitivity of 2.4 V/g at 0° and 180°, while the sensitivity drops to a minimum of 0.02 V/g at the orthogonally aligned 90° and 270° directions. At 800 °C, the directional response

pattern persists, but overall sensitivity decreases, with the maximum sensitivity at 1.2 V/g (corresponding to 0° and 180°) and the minimum sensitivity at 0.01 V/g (corresponding to 90° and 270°). This directional dependency directly stems

from the highly localized asymmetric refractive index modulation structure of the FBG [Fig. 12(b)]. When the vibration direction aligns with the asymmetric axis of the grating (i.e., the long axis direction of the RIMs), the coupling efficiency between the core and cladding modes is highest, resulting in the most sensitive response. Conversely, when the vibration direction approaches the orthogonal direction, the coupling efficiency is lowest, leading to a significant decrease in the sensitivity. Furthermore, the overall sensitivity decline at elevated temperatures aligns with observations in Sections 5.2 and 5.3. The primary physical mechanism involves a decrease in the Young's modulus E of the fiber material with increasing temperatures. As shown in (1), the reduction in E directly leads to a decrease in the sensor's equivalent stiffness. Consequently, the bending deformation generated under the same inertial force diminishes, resulting in reduced acceleration sensitivity.

In summary, this experiment measures the vibration acceleration amplitude at a fixed angle (e.g., $\theta=0^\circ$) or vibration angle at a fixed acceleration (e.g., $a=3g$). However, in actual measurements, the vector sensor outputs a single voltage value containing both the vibration angle and direction information. Mathematically, the sensor output voltage can be modeled as

$$V = S(\theta) \cdot a + V_0 \quad (4)$$

where $S(\theta)$ represents the direction-dependent sensitivity (manifesting as a "8" pattern), a denotes the acceleration magnitude, and V_0 is the bias. For a single measurement V , an infinite number of solutions (a, θ) exist. Therefore, the magnitude and direction of the vibration vector cannot be uniquely determined based solely on the single output V . To achieve fully independent vector decoupling, future systems can be expanded based on our device by integrating three or more of these sensors at specific spatial angles. By establishing a system of equations through multi-channel outputs, the complete

vibration vector can be calculated. The high directional contrast, compactness, and high-temperature stability demonstrated by our sensor make it the ideal component for realizing such advanced solutions.

6. Conclusions

This paper successfully develops a novel high-temperature vector accelerometer based on the femtosecond laser-engraved eccentric FBG and nickel-film reflector. Employing a single-ended reflective structure, the sensor achieves simultaneous demodulation of the vibration amplitude and direction information. Experimental results demonstrate the excellent spectral stability across 25°C – 1020°C , significantly extending the upper operational temperature limit for effective vibration measurement to 800°C . It exhibits excellent linear acceleration response at both the room temperature and 800°C , with sensitivities of 0.169 V/g ($R^2=0.993$) and 0.0743 V/g ($R^2=0.989$), respectively. The frequency response range is 15 Hz – 25 Hz at the room temperature. The 8-shaped angular response curve in polar coordinates clearly validates its stable directional recognition capability across a wide temperature range. The sensor's verified high-temperature performance (stable operation at 800°C) enables it to withstand vibration testing in extreme thermal environments, such as those encountered by hot-end components (e.g., turbine blades) in aeroengines [30]. Simultaneously, its all-fiber, miniaturized design aligns with core requirements for lightweight and electromagnetic interference-resistant sensing units in aerospace structural health monitoring [31], demonstrating strong application potential. Looking ahead, to address challenges like thermal cycling and vibration coupling in real aerospace environments, future research will focus on the engineered packaging design and long-term reliability validation, advancing this technology from proof-of-concept to the practical application.

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Declarations

Conflict of Interest Yiping WANG is an editorial board member for Photonic Sensors and was not involved in the editorial review, or the decision to publish this article. All authors declare that there are no competing interests.

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