

Broadband Fiber-Optic Strain Sensing With Femtoscale Resolution

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Abstract: High-precision strain sensing is pivotal for advancing Earth sciences, structural health monitoring, and biomimetic materials research, yet existing techniques face significant challenges in the simultaneously optimizing bandwidth, sensitivity, and noise floor. Conventional fiber sensors typically operate within narrow frequency bands (<1 kHz) or suffer from significant noise escalation beyond quasi-static regimes. To address this limitation, we introduce an optical frequency comb-based fiber-optic sensing system that enables ultrahigh-resolution strain measurement through advanced heterodyne beating techniques. Our system achieves the simultaneous broadband response (1 Hz–10 kHz) with unprecedented resolution performance, combining a dynamic strain resolution with a noise floor reaching $\sim 1 \text{ f}\epsilon/\sqrt{\text{Hz}}$ over much of the band with 5.25 p ϵ static resolution. Furthermore, the temperature-compensated dual-FFPI (fiber Fabry-Perot interferometer) architecture maintains the high sensitivity throughout the entire frequency band, effectively overcoming the drift limitations of passive fiber sensors. This achievement enables femtoscale resolution strain measurement with flat noise characteristics, permitting the accurate detection of mechanical vibrations across diverse frequency regimes. Our work establishes a new standard for broadband high-resolution sensing, with transformative implications for next-generation geophysical monitoring networks, smart infrastructure systems, and integrated photonic sensing platforms.

Keywords: Optical frequency comb; fiber sensor; strain sensor; laser stabilization

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1. Introduction

Broadband strain sensing – spanning sub-Hz tectonic shifts to kHz-scale structural vibrations – is critical for understanding Earth's dynamics [1], safeguarding infrastructure [2], and advancing

biomimetic materials [3]. Yet, existing technologies exhibit a common limitation: the high resolution is typically confined to high-frequency bands (>1 kHz), while low frequency systems (<100 Hz) suffer from the elevated noise and degraded resolution. This gap impedes applications demanding

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concurrent monitoring of slow deformation, such as seismic [4] or acoustic wave detection [5], and high-frequency events in geophysical networks [6] and structural health monitoring [7].

Recent innovations in optical frequency comb (OFC)-assisted sensing suggest promising solutions: the high phase stability and broadband coherence of OFCs enable ultra-low-noise metrology over wide spectral ranges, making them ideal for translating minute optical phase shifts – such as those induced by strain in a fiber Fabry-Perot interferometer (FFPI) – into resolvable radio-frequency (RF) beatnotes. This approach allows the precise detection of sub-nano-scale strain variations, overcoming fundamental limitations of the conventional laser-based sensors.

The core challenge for broadband strain sensing lies in the decoupling resolution from bandwidth limitations while maintaining system simplicity. In the traditional high-resolution sensing schemes without optical frequency combs, methods such as tracking frequency changes under the strain using Pound-Drever-Hall (PDH) locking [8–11] or demodulating phase shifts between interferometer arms [12–14] can achieve dynamic strain resolution on the order of pε to fε in the high-frequency domain. However, further improvement in the resolution is primarily hindered by two types of noise: the environmental noise leading to the fiber thermomechanical drift and the intrinsic laser frequency noise. The former can be mitigated through temperature control and suppression of mechanically induced disturbances, while the latter may be addressed using ultra-stable optical cavities and optimized servo-locking techniques, such as incorporating acousto-optic modulators (AOMs) [15, 16]. Nevertheless, these approaches still face limitations in achieving both the high resolution and wide sensing range simultaneously. For instance, although systems employing frequency-stabilized lasers and AOMs have demonstrated the remarkable resolution down to 14 fε/√Hz [17], the measurable

strain range remains constrained by the limited tuning range of the AOM. Furthermore, the conventional non-comb schemes also struggle with low-frequency performance due to the laser noise and fiber thermal drift, while high-frequency measurement is limited by the shot noise and detector bandwidth. Although temperature compensation strategies [18] and low-noise laser sources [11] offer partial solutions, they often fall short at a system level. For example, beat-frequency techniques [18], achieve the static resolution around 270 pε but suffer from wavelength-dependent range restrictions.

Recent efforts incorporating OFCs have aimed to improve the sensing bandwidth and resolution, yet many still face trade-offs between complexity, stability, and performance. Dual-comb systems [19–21] map wavelength shifts to radio-frequency comb teeth, offering a large dynamic range for static measurement. However, their resolution is fundamentally bounded by the repetition rate (f_{rep}) and the repetition rate difference (Δf_{rep}). Consequently, they are inherently incapable of capturing the rate of strain variation and cannot perform dynamic sensing. Single-comb systems, on the other hand, have been utilized either as tunable optical sources locked via AOMs or as frequency references to stabilize the sensing laser [8, 22]. The AOM-based approach restricts the measurable dynamic strain range to the AOM bandwidth (typically <200 MHz, corresponding to 1.2 με), while the frequency-reference approach, exemplified by our prior work [22], provides the high absolute frequency readout but lacks intrinsic temperature compensation and is limited to a single sensing arm. Consequently, a unified architecture capable of simultaneous broadband dynamic sensing, high-resolution static readout, and active environmental drift rejection has remained absent. Our prior approach using a single OFC for beat-frequency demodulation achieved a dynamic strain resolution of 87 fε/√Hz at 8 kHz and the

static resolution of 247 pε, representing a notable simplification over dual-comb designs. However, this system still exhibits limitations in the noise floor, frequency range, and long-term stability under environmental fluctuations.

In this work, we introduce a sensing architecture that departs fundamentally from the aforementioned schemes. Rather than using the OFC merely as a static frequency reference or a tunable source, we employ a single semi-stabilized OFC as a coherent bridge linking two actively locked FFPIs. This scheme is designed to simultaneously overcome the limitations of the bandwidth, low-frequency noise, and temperature drift that constrain existing methods. The system incorporates two FFPIs co-located in the same thermal environment: one functions as the sensing element, while the other serves as a reference cavity for real-time cancellation of common-mode temperature fluctuations. To overcome the limited detection bandwidth of the conventional photodetectors – which would otherwise restrict the measurable wavelength separation – we exploit the broadband coherence and high frequency stability of an OFC to bridge the two FFPIs operating at a 3 nm wavelength difference. The sensor system exhibits the ultra-high dynamic resolution of $1 \text{ fε}/\sqrt{\text{Hz}}$. By stabilizing the optical frequency comb to the reference laser and interrogating the beatnote between the sensing laser and the nearest comb tooth, we achieve the static strain resolution of 83 pε. Furthermore, we introduce a novel semi-stabilized comb measurement scheme: with only the repetition rate locked and simultaneous comparison of the beat frequencies from both sensing and reference lasers against the comb enables differential noise suppression, yielding a significantly improved static strain resolution of 5.25 pε. By deliberately allowing f_0 to free-run, its drift noise is canceled in the differential process that actively improves the long-term stability – a strategy that has not been demonstrated in previous OFC-assisted fiber-optic sensors. This

approach effectively mitigates the low-frequency noise while maintaining the high sensitivity across a broad bandwidth, offering a robust and scalable solution for high-fidelity broadband strain monitoring.

2. Results

2.1 Principle of the strain sensor

Figure 1 illustrates the experimental setup and operating principle of the fiber-optic strain sensing system. The key components consist of a continuous-wave (CW) laser, PDH locking modules – including an electro-optic modulator (EOM), mixer, and a servo controller – an FFPI serving as the sensing element, and photodetectors. The FFPI is formed by two fiber Bragg gratings (FBGs), each with the 99% reflectivity and 1 nm optical bandwidth, separated by a 20 cm single-mode fiber segment, yielding a measured cavity linewidth of 1.6 MHz. A piezoelectric transducer (PZT) is attached to the FFPI to introduce calibrated strain signals. By applying sinusoidal voltages of varying frequency and amplitude to the PZT, controlled mechanical deformation is induced, modulating the optical cavity length of the FFPI. A narrow-linewidth CW laser is frequency-stabilized to the FFPI resonance via the PDH technique, ensuring continuous tracking of resonance shifts induced by the external strain. When the axial strain is applied through the PZT, the resultant change in the cavity length alters the resonance frequency, which is transduced into a frequency shift of the locked CW laser. This frequency shift is subsequently detected with the high resolution through optical heterodyne beatnote measurement with an OFC.

Optical fiber sensors are susceptible to the cross-sensitivity between the temperature and strain, making it challenging to isolate the target measured accurately. When the sensor is subjected to the temperature variation ΔT or strain ε , both the

refractive index n and cavity length L of the fiber change, leading to a shift in the resonant frequency ν . The change in the resonant frequency $\Delta\nu$ under the influence of the temperature drift ΔT and strain ε can be expressed as

$$\frac{\Delta\nu}{\nu} = -(\alpha + \xi)\Delta T + (P_\varepsilon - 1)\varepsilon \quad (1)$$

where α is the coefficient of thermal expansion [17], ξ is the thermo-optic coefficient, and P_ε represents the effective elasto-optic coefficient of the optical fiber. This expression indicates that $\Delta\nu$ varies linearly with both the temperature change and applied strain. Based on this model, the theoretical strain sensitivity of the FFPI sensor is calculated to be 151.9 MHz/ $\mu\varepsilon$.

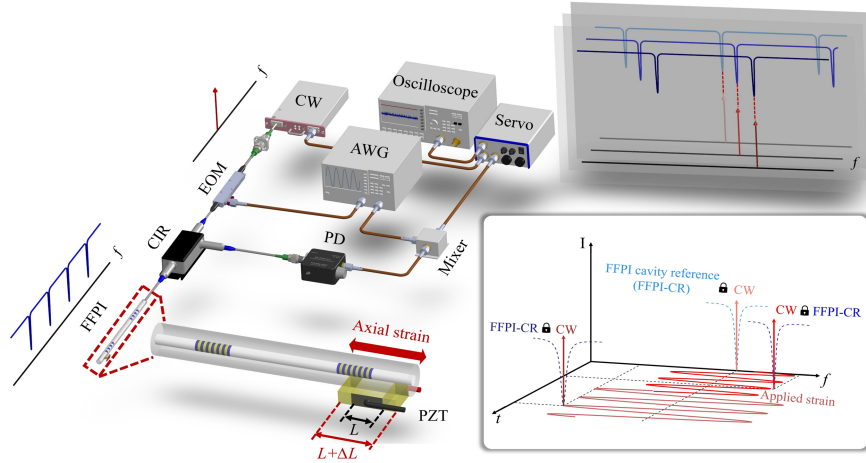


Fig. 1 Schematic of the FFPI-based optical fiber strain sensing system. The inset illustrates the monitoring principle: the frequency of the CW laser is locked and follows the resonant peak shift induced by the applied strain (CIR: optical fiber circulator; AWG: arbitrary waveform generator; Servo: servo controller; PD: photodetector).

2.2 Strain resolution theory

The strain resolution of the sensor is characterized in both dynamic and static regimes, each governed by distinct physical principles and noise limitations. The static resolution R quantifies the minimum detectable static strain and is defined as the ratio of the standard deviation SD of the beat frequency f_{beat} to the strain sensitivity S , i.e.,

$$R = \frac{SD}{S} \quad (2)$$

where SD reflects the frequency instability of the beat signal, which depends on the combined frequency noise of the CW laser and the OFC. Improving f_{beat} stability requires reducing frequency jitter in the CW laser by increasing the frequency discrimination slope D , which is influenced by the feedback control power P_c , probe power P_s , the linewidth $\Delta\nu_{\text{FFPI}}$ of the FFPI, and its reflectivity. Simultaneously, the OFC must be stabilized using high-quality optical and radio-frequency references.

The strain sensitivity $S = \nu_B K$ is determined by the elastic constant K of the fiber (approximately $0.78 \varepsilon^{-1}$ [23]) and the Bragg frequency ν_B of the FFPI. While K is a material property, ν_B can be optimized via the FFPI's operational settings.

To overcome the resolution degradation from the temperature drift and extend the operational bandwidth beyond electronic limits, we propose a novel compensation architecture. It utilizes a reference FFPI and crucially, employs an OFC to bridge a large wavelength gap (~ 3 nm) between the sensing and reference lasers. This approach effectively circumvents the detector bandwidth bottleneck inherent in the conventional differential detection schemes.

In contrast, the dynamic strain resolution is described by the strain power spectral density $S_\varepsilon(f)$, given by [18]

$$S_\varepsilon(f) = \frac{S_{\Delta\nu}(f)}{(\nu_B K)^2} = \frac{S_\nu(f)}{(\nu_B K D)^2} \quad (\varepsilon^2/\text{Hz}) \quad (3)$$

where $S_v(f)$ is the power spectral density of the error signal, which exhibits a $1/f$ noise behavior dominated by the laser frequency noise and servo control characteristics. The term $v_B K$ represents the transduction efficiency from the frequency fluctuation to the strain signal. A higher discrimination slope D , or a larger v_B , or a greater K , each contribute to improved dynamic resolution by amplifying this denominator. Actively stabilizing the laser, particularly by narrowing its intrinsic linewidth $\Delta\nu_{\text{CW}}$, suppresses the low-frequency noise, while servo optimization reduces high-frequency contributions.

Noise characteristics of the system ultimately limit the resolution in both regimes. The source frequency noise, largely dictated by the laser linewidth, constitutes the major constraint [11, 17, 18, 24], underscoring the importance of low-noise laser sources. Additionally, the intrinsic thermal noise in the fiber [24], prominent below 100 Hz, sets a fundamental bound on low-frequency dynamic performance. Our approach combines a narrow-linewidth laser with an ultra-narrow-linewidth FFPI to achieve the high strain sensitivity and noise suppression, thereby enhancing the resolution in both static and dynamic measurement.

To enhance the resolution, we rationally design the FFPI parameters and optimize the modulation depth, increasing the frequency discrimination slope D by approximately an order of magnitude compared to the conventional designs [22]. This optimization, combined with the use of a narrow-linewidth laser and the OFC-based interrogation, is key to suppressing the low-frequency noise and achieving the simultaneous high resolution and broadband performance reported. The high dynamic strain resolution achieved in this work enables the detection of extremely weak vibrational signals, making it particularly suitable for applications in structural health monitoring, such as identifying incipient damage in aerospace components or civil infrastructures. Furthermore, its broadband

sensitivity down to the femto-strain level facilitates precise measurement in nanomechanical sensing and geophysical exploration, where subtle dynamic deformations must be accurately resolved in the presence of environmental noise.

2.3 Dynamic strain measurement

As derived in the theoretical analysis, the dynamic strain resolution is characterized by the strain power spectral density $S_\epsilon(f)$. The experimental procedure is as follows: a CW laser operating at 1542.3 nm with an output power of 10 mW is frequency-scanned using a 20 Hz and 500 mV_{pp} triangular wave generated by the servo controller. Phase modulation is implemented via an EOM driven by a 60 MHz sinusoidal signal. Through optimization of the relative phase between the RF modulation and the local oscillator, a PDH error signal with a signal-to-noise ratio (SNR) of approximately 25 dB is obtained. The frequency discrimination slope is optimized to 2.2×10^{-7} V/Hz. A high slope D is essential for achieving the superior strain resolution, since $S_\epsilon(f)$ is inversely proportional to D^2 .

Figure 2(a) displays the optimized PDH error signal and the corresponding FFPI transmission signal prior to locking. After the frequency lock is established, the error signal is recorded over a period of 25 s, as illustrated in Fig. 2(b). The standard deviation of the locked error signal is measured to be 35 mV, corresponding to a frequency fluctuation of 159 kHz. For spectral analysis, the error signal is acquired using an oscilloscope at a sampling rate of 5 MSa/s over 2 s, and a fast Fourier transform is applied to derive the frequency-domain noise profile.

The resulting strain power spectral density is shown in Fig. 3. The measured noise floor under no strain is plotted alongside the system's response to the calibrated sinusoidal strain applied at 10 Hz, 100 Hz, 1 kHz, and 10 kHz. Furthermore, the system's response at the upper band limit is

confirmed by applying a 10 kHz strain, verifying the full operational bandwidth from 1 Hz to 10 kHz. Distinct signal peaks are resolved at all these frequencies, with a dynamic strain resolution on the order of $1 \text{ f}\epsilon/\sqrt{\text{Hz}}$. This performance level ($1 \text{ f}\epsilon/\sqrt{\text{Hz}}\text{--}10 \text{ f}\epsilon/\sqrt{\text{Hz}}$) is maintained across the 1 Hz to 10 kHz band. While environmental disturbances (e.g., mechanical vibrations) elevate the noise floor at specific frequencies, most notably near 1 kHz, the

resolution remains below $10 \text{ f}\epsilon/\sqrt{\text{Hz}}$ throughout the entire range. The discrete peaks above the baseline (e.g., near 1 kHz) are attributed to ambient mechanical vibrations and are not intrinsic to the sensor. The broadband noise floor demonstrates a resolution on the order of $1 \text{ f}\epsilon/\sqrt{\text{Hz}}$ from 10 Hz to 10 kHz. These results confirm an ultralow and broadband noise floor, demonstrating the system's capability for high-resolution dynamic strain sensing.

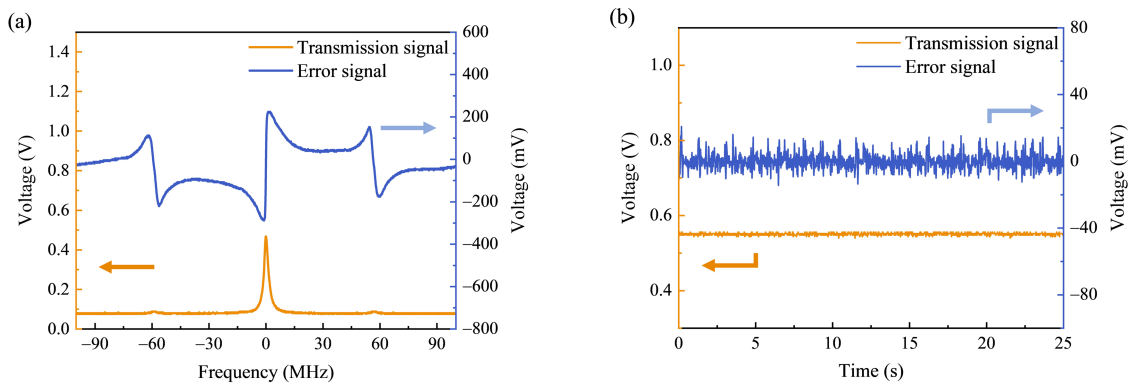


Fig. 2 Dynamic strain measurement results: (a) the error signal (blue) for initial laser frequency locking and the resonant transmission curve of the FFPI (orange), demonstrating the 25 dB SNR, (b) the stabilized error signal and transmitted intensity after locking, confirming that the laser is precisely locked to the resonant peak.

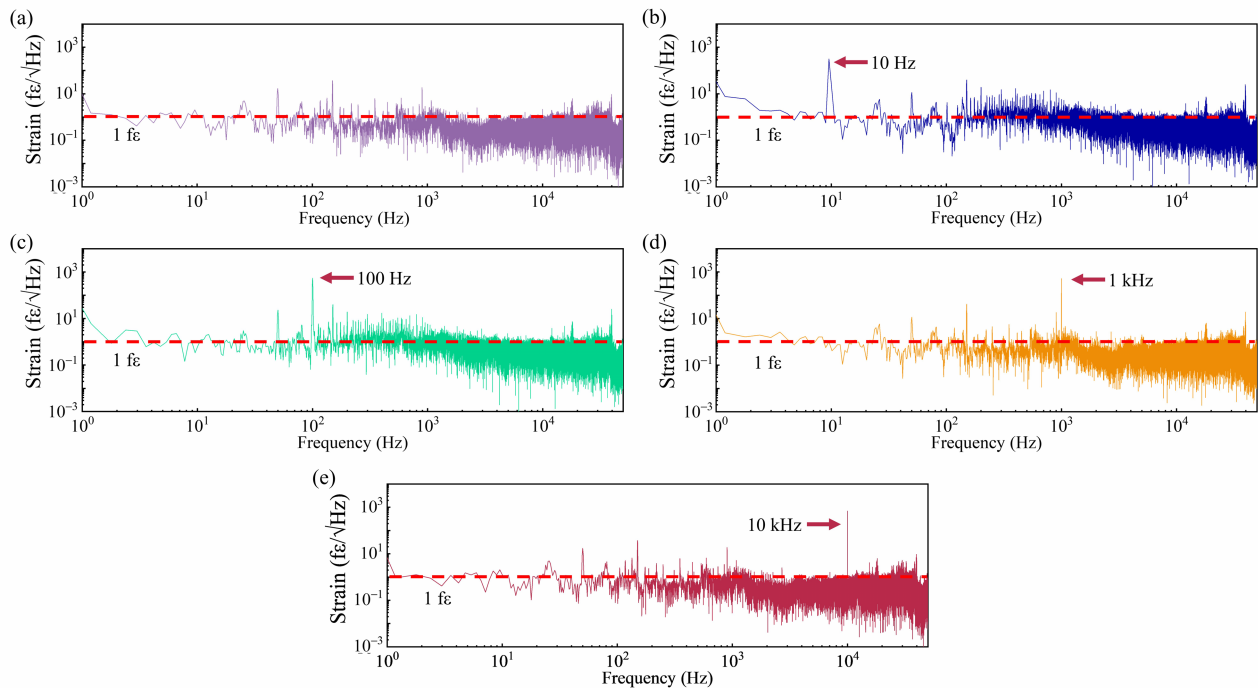


Fig. 3 Power spectral density of the measured strain: (a) the system noise floor under no strain, and (b)–(e) responses to the applied sinusoidal strain at 10 Hz, 100 Hz, 1 kHz, and 10 kHz, respectively (the spectrum confirms the dynamic resolution on the order of $1 \text{ f}\epsilon/\sqrt{\text{Hz}}$ across the 1 Hz–10 kHz band).

2.4 Static strain measurement

To achieve high-resolution static strain sensing with the long-term stability and effective temperature compensation, a dual-laser beat-frequency demodulation scheme is implemented, as illustrated in Fig. 4. This approach enables precise measurement of quasi-static strain events while suppressing the low-frequency noise and thermal drift [22].

The system incorporates two narrow-linewidth CW lasers: a sensing laser (CW_{sensing} at 1 539 nm) locked to the sensing FFPI, and a reference laser

(CW_{Ref} at 1 542.3 nm) stabilized to a reference FFPI. The large frequency difference between the two lasers (several hundred GHz) exceeds the conventional photodetector bandwidths. To overcome this limitation, a mode-locked laser-based OFC is introduced [25]. The OFC, centered at 1 535 nm with a 3-dB bandwidth of 14 nm and a repetition rate of 97.366 MHz, is filtered and optically heterodyned with both CW lasers. As shown in Fig. 4(a), the OFC is phase-locked to CW_{Ref} , ensuring that any frequency shift of the reference laser is transferred to the carrier-envelope offset frequency (f_0) of the comb.

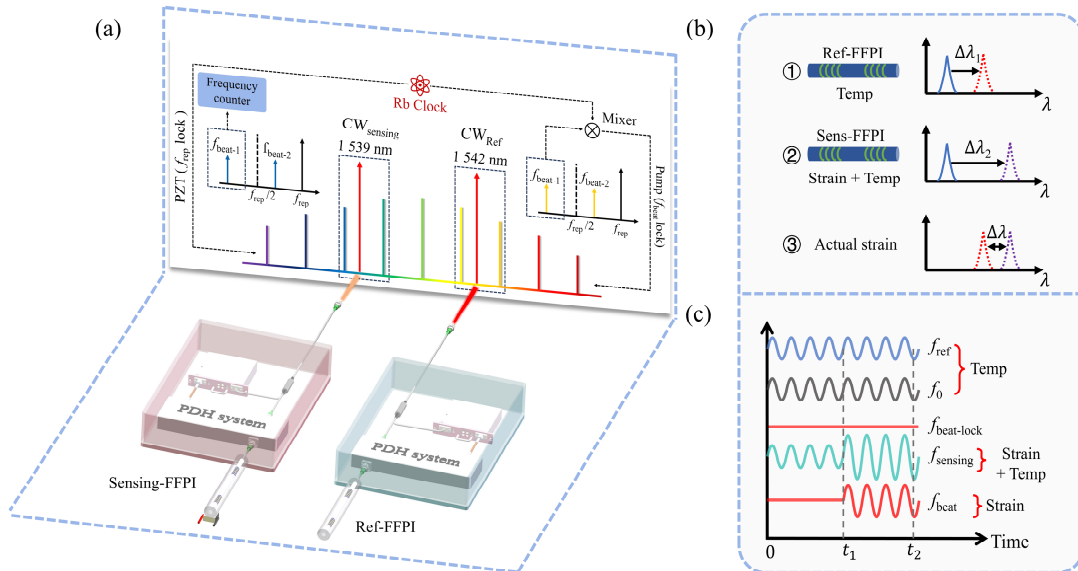


Fig. 4 Principle of static strain measurement with temperature compensation: (a) the experimental setup of the dual-FFPI sensor system based on the OFC (the sensing FFPI is sensitive to both the strain and temperature, while the reference FFPI is primarily sensitive to temperature only), (b) the compensation principle: simultaneous strain and temperature effects on the sensing FFPI are isolated by subtracting the reference FFPI's temperature response, yielding pure strain measurement, and (c) the schematic output signals illustrating the system response under three conditions: the temperature variation only (providing the compensation baseline), combined strain and temperature stimuli, and the final isolated strain measurement after temperature compensation (Temp: temperature; Sens: sensing; Ref: reference).

A key challenge in static strain sensing is the discrimination of strain-induced signals from temperature-related drifts, particularly given the high thermal sensitivity of the sensor (~ 1.2 GHz/ $^{\circ}\text{C}$). To address this, a reference FFPI (resonance at 1 542.3 nm and linewidth 1.6 MHz) is used alongside the sensing FFPI (1 539.4 nm and linewidth 11.9 MHz). A minor difference in temperature sensitivity (~ 2 MHz/ $^{\circ}\text{C}$) exists between

the two FFPIs due to their slightly different Bragg wavelengths. However, under our stable experimental conditions, the resultant strain error (< 70 pe) is below the system's resolution floor and therefore negligible for the reported measurement. When both cavities experience the same thermal environment, as depicted in Fig. 4(b), temperature variations induce identical resonance shifts in both FFPIs. Consequently, the beat note between the OFC

and CW-1 remains unaffected by thermal fluctuations, as confirmed in Fig. 4(c) over the interval $0-t_1$. When the strain is applied to the sensing cavity (t_1-t_2), the resulting differential frequency shift is directly converted into a measurable change in Sensing- f_{beat} , enabling temperature-compensated static strain detection with the high accuracy and minimal low-frequency noise.

This configuration not only extends the measurable frequency range beyond electronic bandwidth limits but also significantly enhances the long-term stability, making it suitable for applications requiring continuous structural health monitoring under varying environmental conditions.

3. Data analysis

Building upon the theoretical framework established earlier, the static strain resolution is evaluated through the optical beat-frequency measurement using both fully stabilized and semi-stabilized optical frequency combs. In the optical heterodyne detection scheme, the beat spectrum within one repetition rate span of the OFC reveals the repetition frequency and a pair of conjugate beatnotes (f_{beat1} and f_{beat2}), which satisfy $f_{\text{beat1}} + f_{\text{beat2}} = f_{\text{rep}}$. A key advantage of this conjugate pair is its robustness to the frequency drift: even if the CW laser frequency shifts beyond one f_{rep} due to the strain or environmental factors, an identical pair of beat signals is still generated. This enables continuous tracking of the CW laser frequency shift via a frequency counter. By converting the optically sensed strain, manifesting as laser frequency variation, into radio-frequency beat signals, the system allows practical and real-time strain monitoring with simple electronic measurement.

The fully stabilized OFC, with the repetition rate locked to an RF reference and a comb mode is locked to a CW reference, is heterodyned with the sensing laser to produce a beat signal (sensing- f_{beat}). As shown in Fig. 5(a), the stabilities of f_{rep} and f_{beat} are characterized by Allan deviations of 0.33 mHz

and 1.2 kHz, respectively, corresponding to fractional instabilities of 3.4×10^{-12} and 6.3×10^{-12} at 1 s. While the f_{rep} stability is improved over time, f_{beat} exhibits a gradual increase in the instability, primarily due to the thermal drift in the sensing laser frequency caused by temperature fluctuations in the Fabry-Perot cavity.

To obtain accurate resolution results, we first calibrate the strain sensitivity of the FFPI. By measuring the change in the free spectral range of the FFPI, the cavity length variation ΔL corresponding to the applied PZT voltage is determined. The experimental results indicate that the strain sensitivity of this sensor is approximately 200 MHz/ $\mu\epsilon$. The experimentally calibrated value aligns reasonably well with the theoretical prediction. The slight discrepancy may be attributed to practical factors such as system losses and the effectiveness of the fiber bonding. To verify the reliability of the experimental data, Fig. 5(c) presents the frequency variations in response to the sinusoidal strain generated by the PZT.

Figure 5(b) presents the Sensing- f_{beat} signal under different conditions. Without applied strain, the beat frequency fluctuated around 20 MHz over 60 min without the significant long-term drift, confirming effective temperature compensation. The standard deviation of the signal is 50.6 kHz over 100 s, corresponding to the static strain resolution of 263 p ϵ . Over a shorter 10 s interval, the standard deviation reduces to 16.59 kHz, yielding a resolution of 83 p ϵ . The residual drift in the long-term measurement is attributed primarily to intrinsic frequency jitter of the sensing laser, which could be further suppressed by narrowing the laser linewidth and the resonance linewidth of the sensor FFPI.

Notably, the fully-stabilized scheme measures the absolute beat frequency, whose noise includes contributions from all components. For enhanced rejection of the common-mode drift, the subsequent semi-stabilized scheme performs the differential measurement.

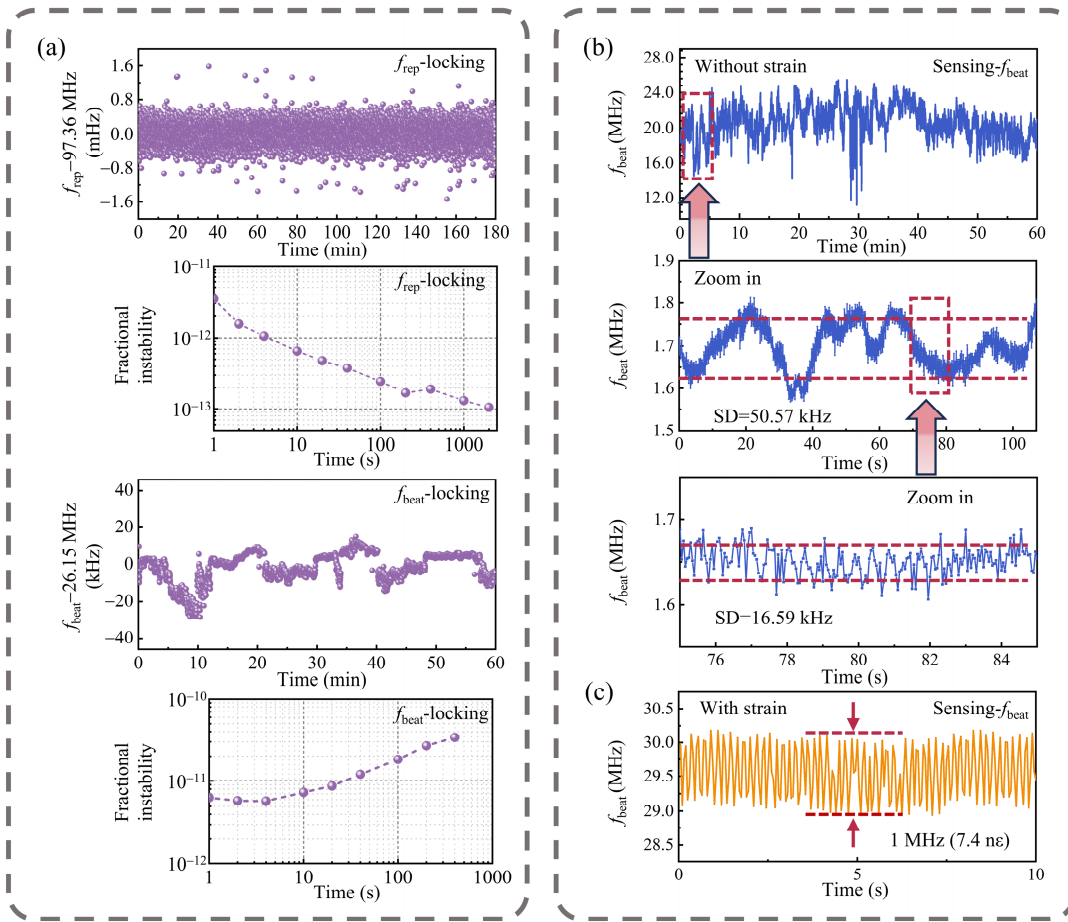


Fig. 5 Static strain measurement results based on the fully-stabilized OFC: (a) stability of the fully-stabilized comb: repetition rate (f_{rep} , top) and optical heterodyne beatnote frequency (f_{beat} , bottom) with their corresponding fractional frequency instability (the Allan deviation), (b) measured optical beatnote frequency under the zero strain condition, demonstrating the high stability, and (c) optical beatnote frequency variation in response to a periodically applied strain, confirming the sensor's response.

To improve the long-term stability, a semi-stabilized OFC is implemented, wherein only f_{rep} is locked, and f_0 is allowed to drift. Figures 6(a) and 6(b) illustrate the operational principle of the fully-stabilized and semi-stabilized OFCs, respectively. In the semi-stabilized scheme, the OFC is simultaneously beat with both the reference and sensing lasers. In this scheme, the free-running f_0 drift acts as the common-mode noise. Differencing the two beat frequencies (Sensing- f_{beat} -Ref- f_{beat}) effectively cancels this drift, yielding a stable differential signal (Δf_{beat}) that isolates the strain-induced shift. As shown in Fig. 6(c), the beat signal between the semi-stabilized OFC and the reference laser over 0 s–20 s exhibits a measured frequency jitter of 516.9 kHz, arising mainly from

the drift in the OFC's offset frequency. The standard deviation of the sensing beat signal (SD_1) is 30.18 kHz, and that of the reference beat (SD_2) is 29.13 kHz. Subtracting the reference beat from the sensing beat gives the differential result (ΔSD) of 1.05 kHz, corresponding to the static strain resolution of 5.25 pε.

Although the semi-stabilized approach exhibits the higher noise under rapid f_0 variations, it remains effective for stable strain extraction and offers significantly improved simplicity and reduced hardware requirements compared to the fully locked system. This method provides a promising alternative for environments with slow thermal variations, highlighting a new direction for practical high-resolution strain sensing.

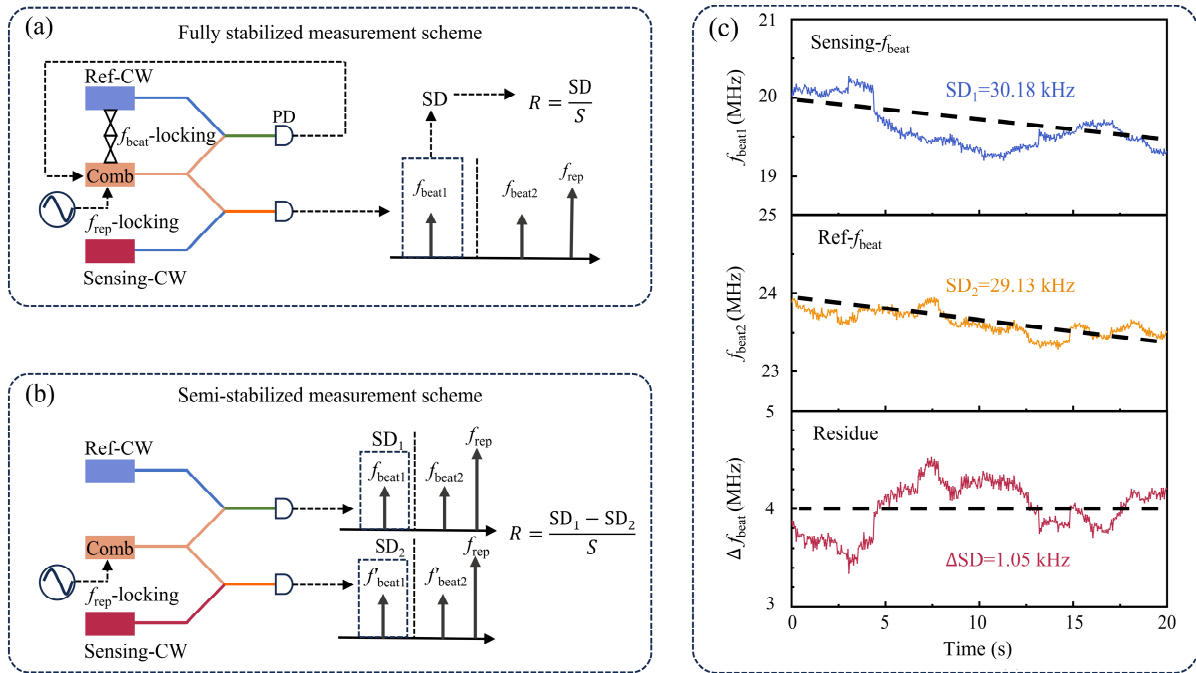


Fig. 6 Static strain measurement using a semi-stabilized optical frequency comb. The schematic diagram of (a) fully-stabilized and (b) semi-stabilized measurement setups, and (c) the time trace of the beat frequency between the sensing laser (top), reference laser (middle), and the optical comb (the bottom figure shows the differential beat frequency signal obtained by subtracting the $\text{Ref-}f_{\text{beat}}$ from the $\text{Sensing-}f_{\text{beat}}$; this final output cancels out common-mode noise, and the standard deviation of its baseline determines the static strain resolution).

4. Discussion

In this study, we have developed an ultrahigh-resolution optical fiber strain sensing system utilizing an OFC, achieving both the broadband detection capability and exceptional noise-limited resolution across static and dynamic regimes. Leveraging the inherent advantage of optical beat frequency conversion, our method translates optical frequency variations into measurable RF, combined with the reference fiber sensor temperature compensation. This enables strain measurement by directly monitoring shifts in the RF frequency, thereby mapping the optically induced frequency changes. In this experimental scheme, the ultimate sensing beat frequency is influenced by the tripartite stability of: 1) the reference laser frequency, 2) the OFC, and 3) the sensing laser frequency. Laboratory testing yields the minimum static strain resolution of 83 pε over a 10 s measurement interval. The fundamental limit of

the resolution in our system is constrained by the intrinsic thermal noise in the optical fiber, which exhibits a $1/f$ spectral behavior below 1 kHz and transitions to spontaneous thermal wave dominance at higher frequencies [17]. The system's ability to maintain the femtoscale resolution from 1 Hz to 10 kHz demonstrates effective suppression of diverse noise sources (low-frequency $1/f$ noise and high-frequency shot noise) that typically constrain the bandwidth-resolution performance of fiber sensors.

Compared to our prior implementation where the OFC served strictly as a frequency standard [22], the present differential architecture leverages the comb as a coherent link for common-mode noise rejection. This shift transforms the measurand from an absolute frequency to a thermally compensated differential beat note, which enables the simultaneous achievement of both the femtoscale dynamic resolution and picoscale static resolution within a unified and single-comb architecture.

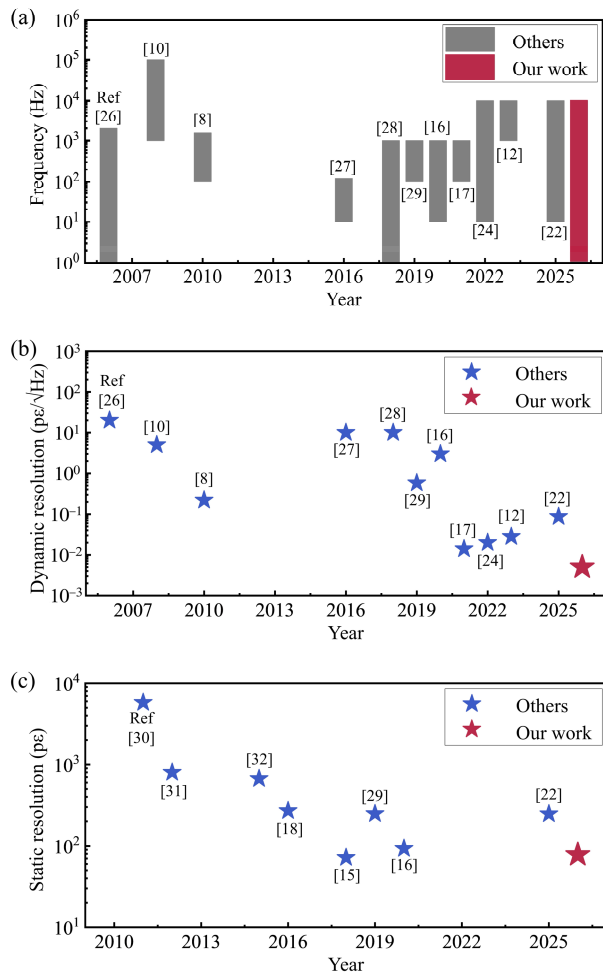


Fig. 7 Performance comparison of the proposed fiber sensor with previously reported results: (a) achieved dynamic strain sensing range compared to other sensing systems, (b) measured dynamic strain resolution, and (c) measured static strain resolution in this work and values reported in the literature.

As summarized in Fig. 7(a), although some previously reported systems have a wide frequency coverage range or excellent resolution under specific conditions [26–28], our method simultaneously achieves the extremely large bandwidth and ultra-high resolution, enabling high-sensitivity operation from quasi-static conditions up to several kilohertz. Meanwhile, as depicted in Fig. 7(b), the resolution of state-of-the-art sensors has continuously improved over the past decade [15, 30–32].

The comparison is based on the best-reported resolution values from each work. Notably, even when evaluated at a common frequency (e.g.,

100 Hz), our system’s performance remains highly competitive, underscoring its broadband low-noise advantage. The current upper frequency limit of 10 kHz is primarily set by the bandwidth of the PZT actuator used for the calibrated strain application. The core optical detection scheme possesses a much higher intrinsic bandwidth, suggesting a pathway to extend the operational range to MHz frequencies with suitable high-speed actuation. Our system not only reaches the femto-strain-level resolution in dynamic measurement but also maintains the pico-strain resolution in static sensing, offering a combination of the bandwidth and sensitivity that is competitive with the most advanced platforms.

The linewidth difference between the sensing and reference FFPIs (11.9 MHz vs. 1.6 MHz) leads to a difference in their PDH locking stability. This contributes to the independent noise floors of the two arms. However, because our temperature compensation relies on differential measurement, the common-mode thermal drift is still effectively rejected. Further performance improvement could be achieved by matching both arms with narrower-linewidth lasers and cavities, which would reduce the baseline noise of each arm prior to differential cancellation.

The fundamental theoretical limit is set by the intrinsic thermal noise of the optical fiber [33–35]. As shown in Fig. 8, the measured system background noise (blue curve) is compared with the theoretical predictions for thermomechanical noise (red) and thermodynamic noise (green). Below 10 Hz, the noise floor follows a distinct $1/f$ trend characteristic of thermomechanical fluctuations. Above 10 Hz, the measured noise converges toward the flat thermodynamic noise limit, indicating that the system operates near the fundamental fiber thermal boundary in this band.

Before reaching the intrinsic fiber thermal noise limit, the primary residual limitation below 10 Hz stems from the laser frequency noise and residual

servo error. To bridge this remaining gap and approach the sub-femto-strain regime, several targeted improvements are feasible: 1) employing a narrower-linewidth sensing laser or an auxiliary pre-stabilization cavity to suppress the low-frequency laser jitter; 2) moderately increasing the FFPI finesse within the locking stability margin; 3) optimizing the PDH modulation depth to further enhance D ; 4) implementing advanced servo architectures to attenuate the residual $1/f$ noise. With these refinements, an order-of-magnitude improvement in resolution is realistically attainable.

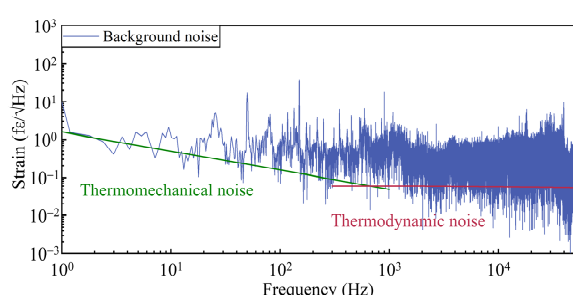


Fig. 8 Measured system background noise (blue) and theoretical noise (green and red).

Looking forward, the capability to perform high-resolution and broadband strain sensing opens new possibilities in multiple fields. In geophysics, it promises enhanced monitoring of seismic activity and crustal deformation. In industrial applications, it can detect subtle mechanical failures in the critical infrastructure or battery expansion in energy storage systems. The dual advantages of the bandwidth and resolution position this technology as a powerful tool for both the scientific research and industrial diagnostics, with the particular value in scenarios requiring long-term, stable, and high-precision strain monitoring.

5. Methods

The FFPI sensing element is fabricated using two FBGs centered at 1539.4 nm and spaced 20 cm apart in a single-mode fiber. Each FBG exhibits the reflectivity of 95% and a bandwidth of 1 nm, resulting in a cavity linewidth of 11.9 MHz. The sensing fiber is pre-tensioned and mounted between

two displacement platforms, with a PZT (providing a maximum displacement of 9 μm at 150 V) affixed to one end to apply the calibrated strain, equivalent to the 27 $\mu\epsilon$ axial strain. The sensing and reference FFPI units are physically separated and mechanically isolated on independent mounts to prevent any direct transfer of the dynamic strain from the sensing to the reference cavity. The entire sensor assembly is enclosed in a sealed insulation box to mitigate environmental acoustic and thermal disturbances. The CW laser (operating near 1539.4 nm) is phase-modulated at 60 MHz using an EOM and directed into the FFPI via an optical circulator. The reflected light is collected by a PD (bandwidth: 125 MHz) and passes through a 0 MHz–32 MHz band-pass filter to suppress conjugate beatnote interference. The filtered RF signal is mixed with the EOM drive signal to produce an error signal, which is processed by a servo controller (Newport LB1005, USA) to stabilize the laser frequency to the cavity resonance. For heterodyne detection, a home-built mode-locked laser-based OFC with a central wavelength of 1535 nm and a 3 dB bandwidth of 15 nm is used. The OFC output is filtered by an FBG before being combined with the strain-shifted CW light on a photodetector for beatnote acquisition.

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Declarations

Conflict of Interest The authors declare that they have no competing interests.

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Use of AI Statement None.

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