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High-Resolution Fiber-Optic Sensing Based on Self-Mode-Locked Optoelectronic Oscillator

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ABSTRACT

High-precision fiber-optic sensing is essential for advanced optical metrology and structural health monitoring; however, conventional techniques are often limited by insufficient sensitivity, demodulation errors, and system instability. To address these challenges, in this work, we propose a high-resolution fiber-optic sensing scheme based on a self-mode-locked optoelectronic oscillator (OEO) incorporating an envelope-free virtual Vernier effect. A microwave frequency comb (MFC) generated by the OEO serves as a highly stable and low-noise sensing carrier, while the virtual Vernier mechanism enables precise frequency demodulation without the need for envelope extraction. This design effectively suppresses noise accumulation and minimizes demodulation errors, leading to substantial improvements in sensing precision and repeatability. Experimental results demonstrate a clear performance enhancement over conventional OEO-based sensing schemes. Furthermore, the envelope-free configuration simplifies the system architecture and enhances robustness against environmental perturbations. Overall, this work presents a compact and effective microwave photonic sensing strategy, offering a scalable route toward high-performance and stable fiber-optic sensing for practical engineering applications.

Keywords: Fiber optic sensor; optoelectronic oscillator; Vernier effect; microwave photonics frequency comb; sensitivity enhancement.

1. INTRODUCTION

Fiber-optic sensors (FOS) utilize light as the information carrier and optical fiber as both the transmission medium and sensing element. Owing to their inherent advantages, including high sensitivity, immunity to electromagnetic interference, compact, and capability of operation in harsh environments, FOS technologies have been extensively investigated for applications in structural health monitoring, aerospace systems, and geophysical exploration [1-2]. In scenarios requiring the detection of minute perturbations such as strain, temperature, and vibration, the realization of high-resolution interrogation schemes is of critical importance. Conventional FOS approaches can be broadly classified into intensity-based and wavelength-based interrogation techniques. Compared with intensity-based FOS schemes, wavelength interrogation relies on tracking optical spectral displacement induced by the measurand, which inherently reduces susceptibility to optical power fluctuations and provides superior measurement accuracy and long-term stability [3]. As a result, wavelength-interrogated fiber sensing schemes have been widely adopted in high-precision applications. Nevertheless, traditional wavelength interrogation methods typically exhibit trade-offs among spectral resolution, measurement range, and system complexity. In practice, the achievable performance is often constrained by the limitations of spectral interrogation instruments, where optical spectrum analyzers (OSA) exhibit restricted resolution and relatively slow scanning rates, thus limiting further enhancement of sensing capability.

To address these limitations, microwave photonic techniques have been introduced to enhance the performance of FOS [4]. By mapping optical spectral variations into the microwave frequency domain, microwave photonics transforms wavelength interrogation into a frequency measurement process, enabling significantly improved stability and precision. Among various microwave photonic implementations, optoelectronic oscillators (OEOs) represent a typical scheme for

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optical-to-microwave frequency mapping [5]. In conventional OEO-based sensing systems, the oscillation spectrum consists of a series of equally spaced cavity modes. However, most prior approaches rely on tracking only the dominant oscillating mode with the highest power. Such single-frequency interrogation is susceptible to frequency noise and environmental perturbations, while the weaker side modes are generally not utilized due to their limited signal-to-noise ratio. As a result, the frequency discrimination capability is limited by the reliance on single-mode tracking.

To overcome these limitations, this work proposes and experimentally demonstrates a high-resolution fiber sensing system based on a self-mode-locked OEO-generated microwave frequency comb (MFC). By exploiting the multi-tone and phase-correlated nature of the comb spectrum, the sensing information can be extracted from multiple coherent frequency components simultaneously. Furthermore, by introducing a virtual Vernier effect, the effective frequency discrimination capability is significantly enhanced, enabling resolution beyond that achievable with single-frequency demodulation. This approach combines the intrinsic stability of OEO frequency combs with the resolution amplification property of the Vernier mechanism, providing a compact and scalable solution for next-generation high-resolution fiber sensing.

2. SYSTEM ARCHITECTURE AND OPERATING PRINCIPLE

Fig. 1(a) illustrates the proposed self-mode-locked OEO-based MFC sensing system. A tunable laser (TL) provides a continuous-wave optical carrier, which is intensity-modulated by a Mach-Zehnder modulator (MZM). The modulated light propagates through a 2000-m single-mode fiber (SMF), which acts as a long delay element in the feedback loop. After photodetection (PD), the delayed optical signal is converted back into the electrical domain. The electrical signal is amplified (EA) to compensate loop losses and filtered (EF) to define the oscillation bandwidth before being fed back to the MZM, thereby closing the optoelectronic loop.

The total loop delay determines the spacing of the oscillation modes. For an OEO with a total round-trip delay τ , which includes the optical fiber delay as well as the electrical path delay, the oscillation frequencies satisfy the phase closure condition, leading to a cavity free spectral range (FSR) defined as

$$FSR = 1 / \tau \quad (1)$$

For the self-mode-locked OEO, the FSR is denoted as f_{FSR} , which defines the spacing between adjacent comb lines. The generated MFC therefore consists of equally spaced frequency components expressed as:

$$f_n = f_0 + n f_{FSR} \quad (2)$$

where n is an integer. This comb structure is illustrated in Fig. 1(b).

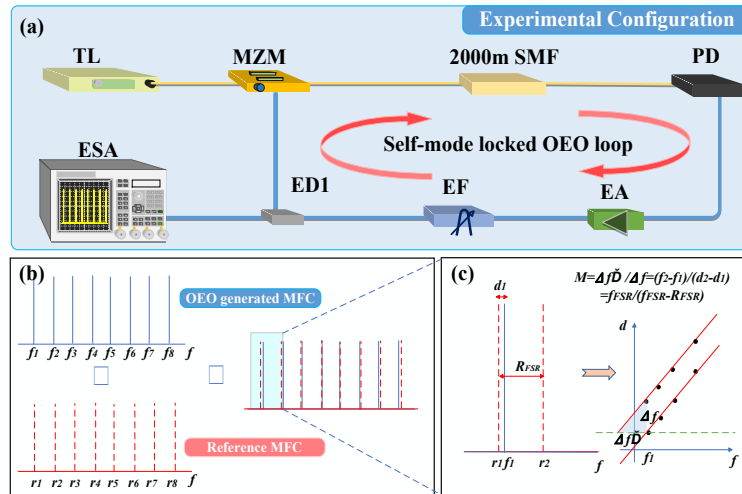


Figure 1. Schematic of the proposed self-mode-locked OEO-based microwave frequency comb sensing system.

To realize the virtual Vernier effect, a reference MFC with a slightly different spacing R_{FSR} is introduced. When the two combs are superimposed, the spacing mismatch [6] :

$$\Delta f = f_{FSR} - R_{FSR} \quad (3)$$

causes the relative alignment between the two comb grids to gradually drift, forming a slowly varying Vernier envelope, as shown in Fig. 1(c). In this case, a small variation in f_{FSR} produces a much larger displacement in the relative position between the two comb structures. The effective magnification factor of this virtual Vernier effect can be approximated as :

$$M = \frac{f_{FSR}}{|f_{FSR} - R_{FSR}|} \quad (4)$$

Therefore, by selecting R_{FSR} close to f_{FSR} , the sensitivity of frequency discrimination can be significantly enhanced, enabling high-resolution sensing without modifying the physical loop structure.

3. EXPERIMENTAL RESULTS AND DISCUSSION

To experimentally verify the proposed self-mode-locked OEO configuration, the setup shown in Fig. 1(a) was implemented. A narrow-linewidth TL (Lucentek TSL-PM-20-C-N-P-FA) was employed as the optical source. The continuous-wave output was modulated by an MZM (EOSPACE) and subsequently injected into a 2000-m single-mode fiber (SMF) delay line, forming a high-Q optoelectronic feedback cavity. The optical signal was detected by a 31-GHz PD (Finisar MPRV1331A), and the electrical signal was amplified by a Mini-Circuits ZX60-242GLN+ amplifier with 25-dB gain. Mode selection was realized using a narrowband EF (RF-Lambda RCF20102025) centered at 2.015 GHz with a 3-dB bandwidth of 20 MHz. The output microwave signal was characterized using an ESA (Keysight E4440A).

When the loop gain slightly exceeded the oscillation threshold, oscillation was established at the frequency where the loop phase condition was fulfilled, resulting in single-frequency operation. As the driving power and loop gain were further increased, the intrinsic cosine-type nonlinear transfer function of the MZM, together with gain saturation in the RF amplifier, drove the system into a nonlinear dynamical regime. Once the operating point crossed the Hopf bifurcation threshold, the previously stable equilibrium lost stability and periodic solutions emerged, leading to multimode oscillation. Under the joint constraints of delayed feedback and narrowband filtering, the excited longitudinal modes gradually established fixed phase relationships, eventually evolving into a stable self-mode-locked state.

Fig. 2(a) presents the measured wide-span microwave spectrum in the self-mode-locked regime. A clear comb-like spectral structure is observed within the frequency range of approximately 1.998–2.006 GHz, corresponding to an overall spectral span of about 8 MHz. The spacing between adjacent comb lines is measured to be approximately 99 kHz, which agrees well with the FSR determined by the 2000-m fiber delay. A zoomed-in view is shown in Fig. 2(b), where multiple equally spaced comb lines can be clearly resolved within a span of approximately 1 MHz. The peak power of individual comb lines is around –20 dBm, while the noise floor remains below –80 dBm, resulting in a spectral contrast of approximately 60 dB.

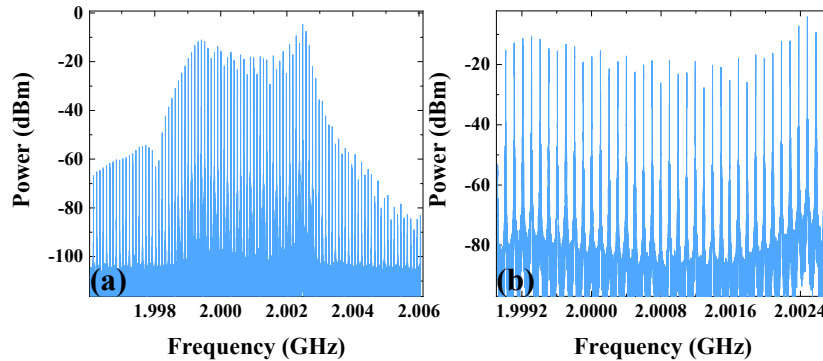


Figure. 2. (a) Measured MFC generated by the self-mode-locked OEO, (b) Enlarged view of MFC.

The implementation of the proposed vernier processing is illustrated in Fig. 3. Figure 3(a) shows the measured MFC generated by the self-mode-locked OEO. To introduce a controlled spacing mismatch without adding hardware complexity, a virtual reference comb with a slightly detuned spacing is numerically constructed and superimposed on the measured comb, as shown by the dashed vertical lines in Fig. 3(b). Due to the intentional difference in comb spacing, the measured comb lines are not exactly aligned with the reference grid markers, forming a vernier-type frequency structure. For each measured comb line f_n in Fig. 3(b), the two adjacent reference markers that bound it are identified. As illustrated in Fig. 3(c), the frequency offset between the measured comb line and the left reference marker is denoted as a , while the interval between the two neighboring reference markers is denoted as b . The normalized ratio a/b defines the fractional position of the measured comb line within the corresponding reference interval. This operation is performed for a sequence of comb lines across the spectrum. Specifically, for each measured resonance frequency f_n , its corresponding normalized fractional position is calculated based on its location within the nearest reference interval. The resulting pairs $(f_n, a_n/b_n)$ form the discrete data points shown in Fig. 3(d). A smooth fitting curve is therefore applied to capture this systematic variation. The intersection of the fitted curve with the zero-reference axis corresponds to the theoretical coincidence frequency between the measured comb and the virtual reference comb, i.e., the frequency at which the two combs would be aligned under ideal compensation of the spacing mismatch.

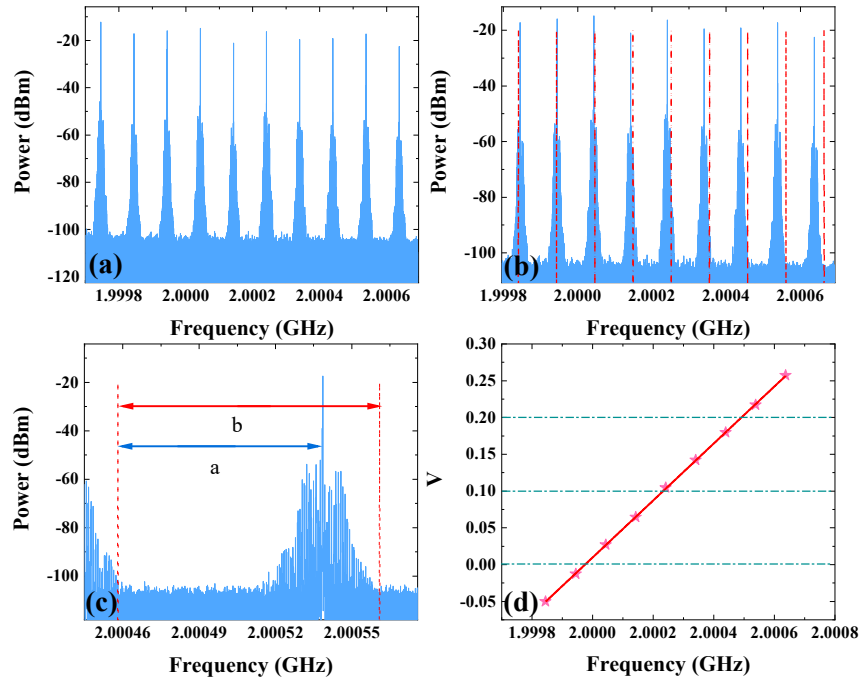


Figure 3. (a) Measured MFC generated by the self-mode-locked OEO. (b) Superposition of the measured comb and the numerically constructed reference comb (dashed lines). (c) Local enlarged view illustrating the relative-position reading of a comb line within one reference interval. (d) Mapped data points and fitted curve used to retrieve the theoretical coincidence frequency.

In OEO-based sensing, external perturbations are reflected as a global translation of the oscillation-frequency comb. To emulate such perturbations in a controlled and repeatable manner, the laser wavelength was swept in fixed steps. The induced comb translation reproduces the frequency-shift behavior expected under practical sensing conditions while offering improved controllability and stability for quantitative evaluation of the vernier amplification effect. Figure 4(a) shows the microwave frequency comb spectra recorded at different laser wavelengths under self-mode-locked operation. Following the procedure described in Fig. 3, a virtual reference comb with a slightly detuned spacing is numerically constructed for each recorded spectrum. The relative fractional positions of multiple comb lines are evaluated and mapped into a normalized coordinate space. The resulting fitted curves are shown in Fig. 4(b). As the laser wavelength increases, the fitted curve undergoes a systematic translation along the frequency axis, and the extracted coincidence frequency exhibits a pronounced drift.

For comparison, Fig. 4(c) shows the directly recorded spectra analyzed without vernier effect. In this case, the frequency shift is obtained by tracking an individual comb line. The observed displacement remains small and corresponds to the intrinsic frequency response of the system to the laser-wavelength variation.

The quantitative comparison is presented in Fig. 4(d). Without vernier processing, the frequency shift exhibits a linear dependence on wavelength with a slope of 6.914 kHz/nm ($R^2 = 0.99992$). When the virtual vernier method is applied, the retrieved coincidence frequency shows a slope of 178.525 kHz/nm ($R^2 = 0.99995$). This corresponds to an amplification factor of approximately 25.8. The amplification originates from the cumulative mismatch between the measured comb spacing and the virtual reference spacing. A small uniform translation of the comb spectrum produces a magnified displacement of the coincidence-frequency readout extracted from the fitted-curve intersection, while preserving the narrow linewidth and high spectral resolution of the original comb modes.

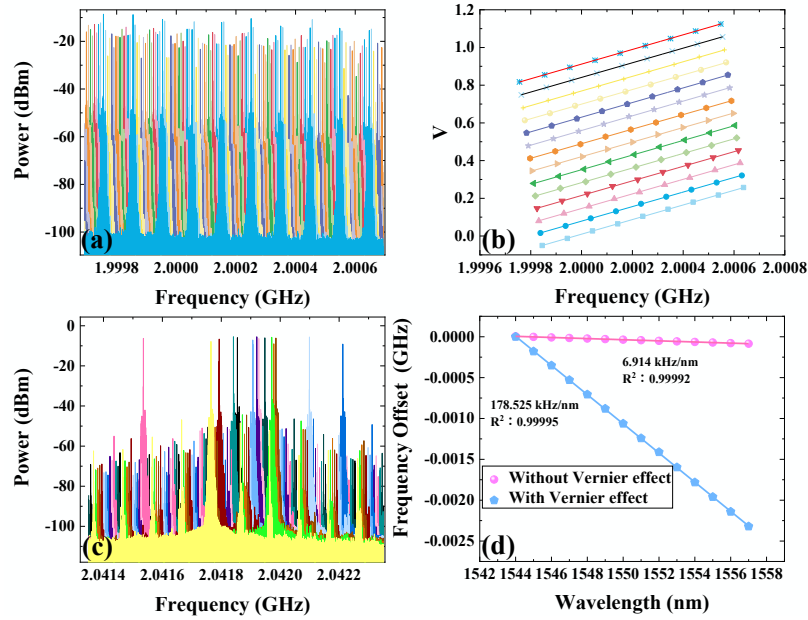


Figure 4. (a) Measured MFC spectra at different laser wavelengths under self-mode-locked operation. (b) Extracted coincidence-frequency shifts obtained using the virtual vernier processing. (c) Frequency spectra analyzed by direct tracking without vernier processing. (d) Linear comparison of frequency shifts with and without vernier amplification.

To evaluate the frequency stability of the self-mode-locked OEO, the microwave spectrum was continuously monitored using an ESA over a 15-minute interval under fixed operating conditions. The Max Hold function of the ESA was enabled to capture the maximum excursion of the monitored comb line during the measurement period. Figure 5(a) shows the measured comb spectrum, where the highlighted region indicates the selected comb line used for stability evaluation. The overall comb structure remains unchanged throughout the measurement duration. A magnified view of the monitored resonance peak is presented in Fig. 5(b). The maximum frequency offset recorded during the 15-minute measurement is approximately 0.24 kHz. No observable linewidth broadening or mode hopping is detected, indicating stable self-mode-locked operation.

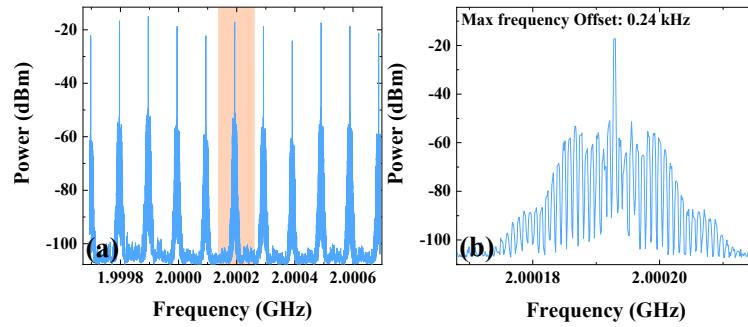


Figure 5. (a) Frequency stability of the self-mode-locked OEO. (b) Enlarged view of the selected comb line showing the observed frequency deviation.

4. CONCLUSION

In this work, a self-mode-locked OEO-based MFC incorporating an envelope-free virtual vernier processing scheme has been demonstrated. By directly exploiting discrete comb-line positions in the frequency domain, the proposed method eliminates the need for physical reference loops and envelope fitting while preserving the high spectral resolution of the original comb structure. A controlled laser-wavelength variation was employed to emulate sensing-induced frequency shifts, and a sensitivity enhancement factor of approximately 25 was experimentally verified. The system maintains stable self-mode-locked operation with a maximum frequency deviation of 0.24 kHz over a 15-minute interval. The proposed frequency-domain vernier scheme provides an efficient and hardware-simplified approach for enhancing the resolution of frequency-shift-based OEO sensors, and offers potential for high-precision microwave photonic sensing applications.

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