

Optoelectronic Oscillator-Enabled Fiber Optic Fabry-Pérot Ultrasonic Sensor

Weixuan LUO^{1,2}, Baiqing NAN^{1,2}, Weijia BAO^{1,2}, Dezhi ZHU^{1,2}, Dejun LIU^{1,2}, Ying WANG^{1,2}, Yiping WANG^{1,2}, Changrui LIAO^{1,2*}, and Xiaoxia CHEN^{3*}

¹Shenzhen Key Laboratory of Ultrafast Laser Micro/Nano Manufacturing, State Key Laboratory of Radio Frequency Heterogeneous Integration, Shenzhen University, Shenzhen 518060, China

²Key Laboratory of Optoelectronic Devices and Systems of Ministry of Education and Guangdong Province, College of Physics and Optoelectronic Engineering, Shenzhen University, Shenzhen 518060, China

³Department of Radiology, The Third Medical Centre, Chinese PLA General Hospital, Beijing 100039, China

*Corresponding authors: Changrui LIAO and E-mails: cliao@szu.edu.cn and

Xiaoxia CHEN

chenxiaoxia@301hospital.com.cn

Abstract: Fiber-optic ultrasound sensors hold considerable promise for diverse applications, benefiting from their high sensitivity and advantageous physical characteristics. However, their practical adoption is often hindered by the operational instability of conventional high-speed demodulation techniques, which rely on sideband filtering and require active quadrature-point locking. To address this fundamental constraint, this work introduced a high-sensitivity Fabry-Pérot (FP) fiber-optic ultrasound sensing system incorporating an optoelectronic oscillator. The system integrated a submicron-precision Fabry-Pérot microcavity, fabricated on the fiber tip via two-photon polymerization (TPP), with a low-phase-noise optoelectronic oscillator (OEO) of excellent frequency stability. Experimental characterization demonstrated ultrasonic sensitivity of 3.089 mV/kPa at 1 MHz and low noise-equivalent pressure of 168 Pa, achieved without high-reflectivity coatings. By merging fiber-optic sensing with microwave photonics, the proposed architecture eliminated the need for active sideband locking, thereby substantially improving operational stability in complex and dynamic environments. This advancement establishes a reliable technical pathway for precision applications including structural defect mapping, intravascular photoacoustic imaging, and underwater acoustic holography.

Keywords: Optical fiber sensor; Fabry-Pérot sensor; ultrasonic sensor; optoelectronic oscillator; two-photon three-dimensional (3D) printing

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1. Introduction

The growing demand for the ultrasound technology in biomedical imaging [1], industrial nondestructive testing [2, 3], gas detection [4], and

underwater detection [5] has driven the evolution of ultrasonic transducers. Conventional piezoelectric transducers (PZTs), while widely used, face inherent limitations, including the susceptibility to electromagnetic interference, bulky configurations,

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and restricted sensitivity, particularly in confined or harsh environments [6, 7]. Fiber-optic ultrasonic sensors, benefiting from miniaturization, multiplexing capability, and immunity to electromagnetic interference, have emerged as a promising solution to address these challenges [8–11].

Current fiber ultrasonic sensor architectures primarily comprise π -shifted Fiber Bragg gratings (π -FBGs) [12], Fabry-Pérot interferometers (FPIs) [13, 14], whispering gallery mode (WGM) resonators [15], and various interferometric configurations [16, 17]. Notably, two-photon polymerization (TPP) based microfabrication [18, 19] has significantly enhanced ultrasound sensitivity by enabling nanoscale precision in microcavity fiber sensors [20–22], making them ideal for minimally invasive biomedical diagnostics and high-resolution structural health monitoring. However, conventional demodulation techniques often rely on sideband-filtered intensity-based approaches to extract ultrasonic signals [23–25]. This methodology demands precise stabilization of the spectral signature, which constrains the system's dynamic range and heightens its susceptibility to environmental interference. This is a particularly critical issue for three-dimensional (3D)-printed polymer-based sensors, as their inherent thermo-mechanical instability significantly exacerbates temperature-induced signal drift, ultimately undermining measurement reproducibility. Consequently, the concurrent demands for high-speed demodulation sustainability and robust signal integrity underscore the need for the development of innovative technological approaches. Emerging optoelectronic oscillator (OEO) methodologies address this challenge by transducing optical phase modulation into frequency-stabilized microwave signals through hybrid photonic electronic resonance, circumventing wavelength locking constraints and calibration-induced inaccuracies [26].

In recent years, fiber sensors based on optoelectronic oscillators have demonstrated remarkable precision in static parameter measurement [27], achieving temperature resolution of $0.0629\text{ }^{\circ}\text{C}$ [28], refractive index sensitivity of $1.32 \times 10^{-3}\text{ RIU}$ [29], and strain resolution of $0.3 \times 10^{-3}\text{ }\mu\epsilon$ [30]. These advancements stem from the OEO's unique capability to detect minute variations in fiber properties, establishing a robust physical foundation for ultra-sensitive sensing. Furthermore, OEOs exhibit exceptional performance in dynamic sensing applications. Comparative studies reveal their superior spectral resolution over conventional interferometers in acoustic sensing [31]. Advanced techniques, such as optical injection, enable the phase sensitivity of 1.31 rad/V in the 2 kHz frequency band [32], while the acousto-optic modulator (AOM)-assisted carrier sideband separation combined with the Michelson interferometry achieves the vibration amplitude sensitivity of 1.77 GHz/cm and sub-nanometric displacement resolution of 5.1 pm [33]. These results underscore the OEO's potential as high-performance dynamic sensors. However, despite these achievements, the integration of the OEO technology with Fabry-Pérot (FP)-based ultrasonic sensors remains largely unexplored. Current applications predominantly focus on low-frequency vibration detection, leaving the untapped potential of OEOs in high-frequency ultrasonic sensing yet to be fully realized.

In this work, we demonstrated a high-sensitivity fiber FP ultrasonic sensing system incorporating an OEO. The system featured an FP microcavity with a thin-film hollow structure directly fabricated on the fiber tip via femtosecond laser-induced two-photon polymerization. By effectively translating ultrasonic perturbations into modulation on a high-stability microwave carrier generated by the OEO, our system enabled highly sensitive and noise-resilient signal demodulation. The sensor achieved the outstanding ultrasonic sensitivity of 3.089 mV/kPa

at 1 MHz, demonstrating not only the high signal responsivity but also remarkable robustness against environmental temperature fluctuations. The practical feasibility of the system is further verified through successful ultrasonic scanning imaging experiments, underscoring its significant potential for real-world high-precision acoustic sensing applications.

2. Ultrasonic sensor probe

Figure 1(a) illustrates the proposed FP cavity resonator structure. The FP cavity resonator was fabricated on the fiber end face using high-precision

TPP 3D printing. A sealed FP resonator design with a $d=13\ \mu\text{m}$ photoresist release channel was adopted to shield the sensor from the liquid interference. The structure was fabricated directly on the end-face of a cleaved single-mode fiber using a commercial two-photon lithography system (PROME-Uni, Magie-nano, China), with the fiber immersed in the photoresist (IP-S, Nanoscribe, Germany). After fabrication, the channel was sealed with ultraviolet (UV) adhesive under a micromanipulator, ensuring environmental isolation and mechanical stability. The inset in Fig. 1(a) shows a photograph of the corresponding prototype.

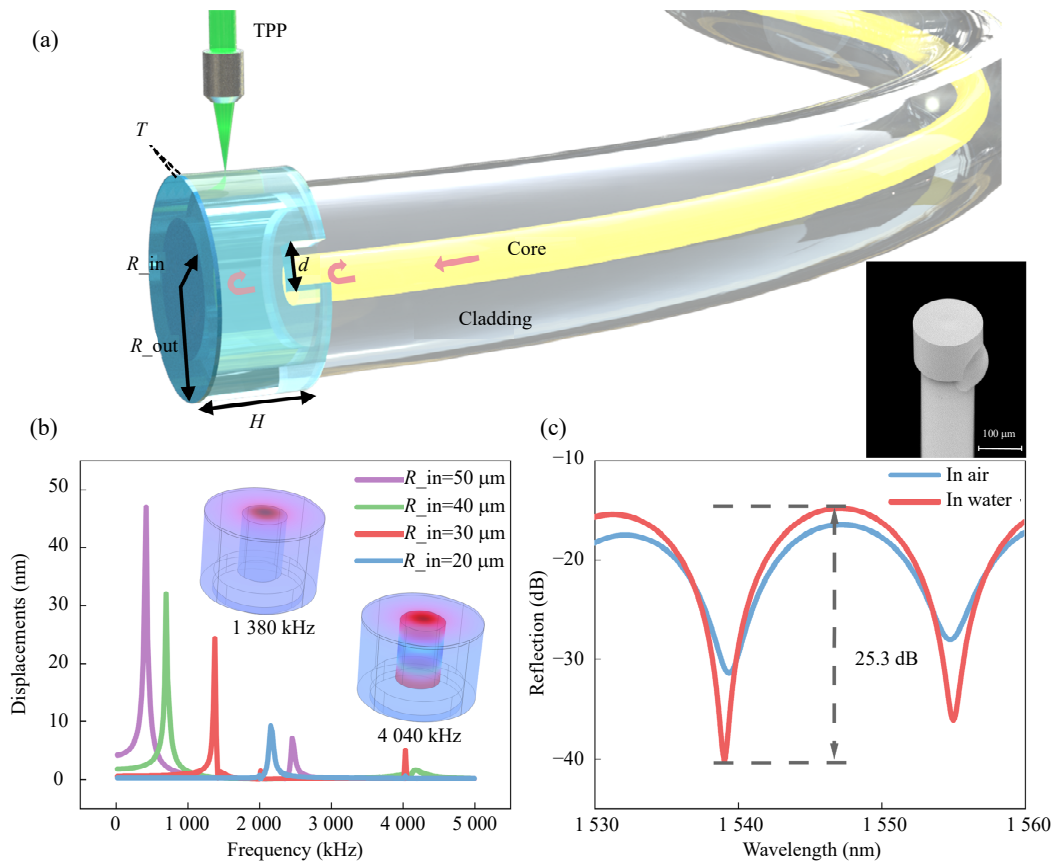


Fig. 1 Design, simulation, and spectral response of the proposed fiber-optic FP sensor: (a) the schematic and scanning electron microscope image of the proposed fiber FP cavity, (b) mode simulation results of the device for acoustic wave sensing in a water environment, and (c) reflection spectra of the sensor in air and water environments.

The precise resonant mode of the structure was numerically simulated using the multiphysics finite element analysis software, with the material parameters set as Young's modulus of 2.1 GPa, Poisson's ratio of 0.3, and the density of 1.19 g/cm³.

As shown in Fig. 1(b), the maximum response frequency varies with different inner diameters under underwater conditions. When the parameters were set to the outer diameter $R_{out}=80\ \mu\text{m}$, the FP cavity height $H=85\ \mu\text{m}$, the end face thickness

$T=3.5\text{ }\mu\text{m}$, and the plane wave acoustic pressure of 500 Pa, the first-order resonant frequency decreased with an increase in the inner diameter. Thus, the target resonant frequency could be achieved by adjusting the inner diameter. Considering both the contact stability between the FP cavity and the optical fiber end face and the need for a higher resonant frequency, an inner diameter of $R_{\text{in}}=30\text{ }\mu\text{m}$ was selected for this experiment. Simulations indicated that the sensor's first-order resonant frequency was 1 380 kHz. A lower-order resonant frequency was also observed at 4 040 kHz. Reflection spectra measured in air and water are shown in Fig. 1(c). The higher refractive index of water significantly increased the end-face reflectivity, resulting in a transmission signal-to-noise ratio of 25.3 dB.

3. Ultrasonic signal demodulation system

In contrast to the conventional optical sideband-filtering-based rapid demodulation method, a high-precision OEO rapid demodulation system was used in this study, as depicted in Fig. 2(a). The optical beam from an amplified spontaneous emission (ASE; 100 mW, Max-ray Photonics Co., Ltd., China) broadband light source was routed through a circulator to the FP sensor for spectral slicing. The reflected light from the FP sensor was then directed through a polarization controller (PC) to adjust its polarization state before entering a Mach-Zehnder modulator (MZM; 10 GHz, Sumitomo, Japan) for radio-frequency (RF) signal modulation. The modulated optical signal was subsequently amplified by an erbium-doped fiber amplifier (EDFA; Highlight, China) and then converted into an electrical signal by a photodetector (PD; 10 GHz, Highlight, China). After amplification by an electronic amplifier (EA; MTC5525; Highlight, China), the signal was filtered by an electrical filter (EF; QBF-5.65, Qualwave, China) with a central frequency of 5.65 GHz and a bandwidth of 20 MHz, and then split into two paths by a power divider (DIV). One path was fed back to

the MZM to form a closed-loop OEO, while the other path was mixed with a frequency generated by a signal generator 2 (SG2) in a mixer to achieve downconversion, yielding a low-frequency and high-sensitivity signal. This signal was ultimately captured and analyzed by a data acquisition card (DAQ).

The operational principle of the proposed fiber ultrasonic sensing system is grounded in the theory of a single-passband microwave photonic filter (MPF), with its core demodulation mechanism being intensity interrogation rather than frequency discrimination. As illustrated in Fig. 2(a), the FP sensor serves as a spectral slicer for the broadband ASE source. The reflected light, carrying the periodic transmission characteristic of the FP cavity, was injected into the OEO loop. The collective response of the FP, MZM, and PD constituted a single-passband MPF, whose central frequency is given by [34]

$$f = \frac{1}{D \times \text{FSR}_{\text{FP}}} = \frac{2n_{\text{eff}}H}{D\lambda^2} \quad (1)$$

where FSR_{FP} denotes the free spectral range of the FP cavity and n_{eff} denotes the effective refractive index within the FP cavity. Owing to the sensor employing a closed-cavity design, n_{eff} is taken as 1 (air). D is the dispersion coefficient of the fiber within the OEO loop, λ is the transmission wavelength, and H is the FP cavity length. This f determines the oscillation frequency of the OEO when the loop gain satisfies the oscillation condition.

Crucially, the system was designed to transduce ultrasonic perturbations into measurable intensity variations of the OEO's microwave output. When an ultrasonic wave impinged upon the FP sensor, it induced dynamic changes in the FP cavity length. This modulation altered the effective coupling efficiency of the spectrally sliced light back into the OEO loop, thereby directly modulating the optical power arriving at the PD. Consequently, this resulted in amplitude modulation (AM) of the generated

microwave signal at the OEO output. Although a concomitant shift in the MPF's central frequency f occurred, the high-frequency stability inherent to the OEO regime rendered this frequency modulation (FM) component less pronounced and more susceptible to environmental noise in the presence of

weak acoustic signals. In contrast, the amplitude modulation component provided a highly sensitive and robust response, which was extracted via in-phase/quadrature (I/Q) demodulation of the OEO's RF output to recover the original ultrasonic waveform.

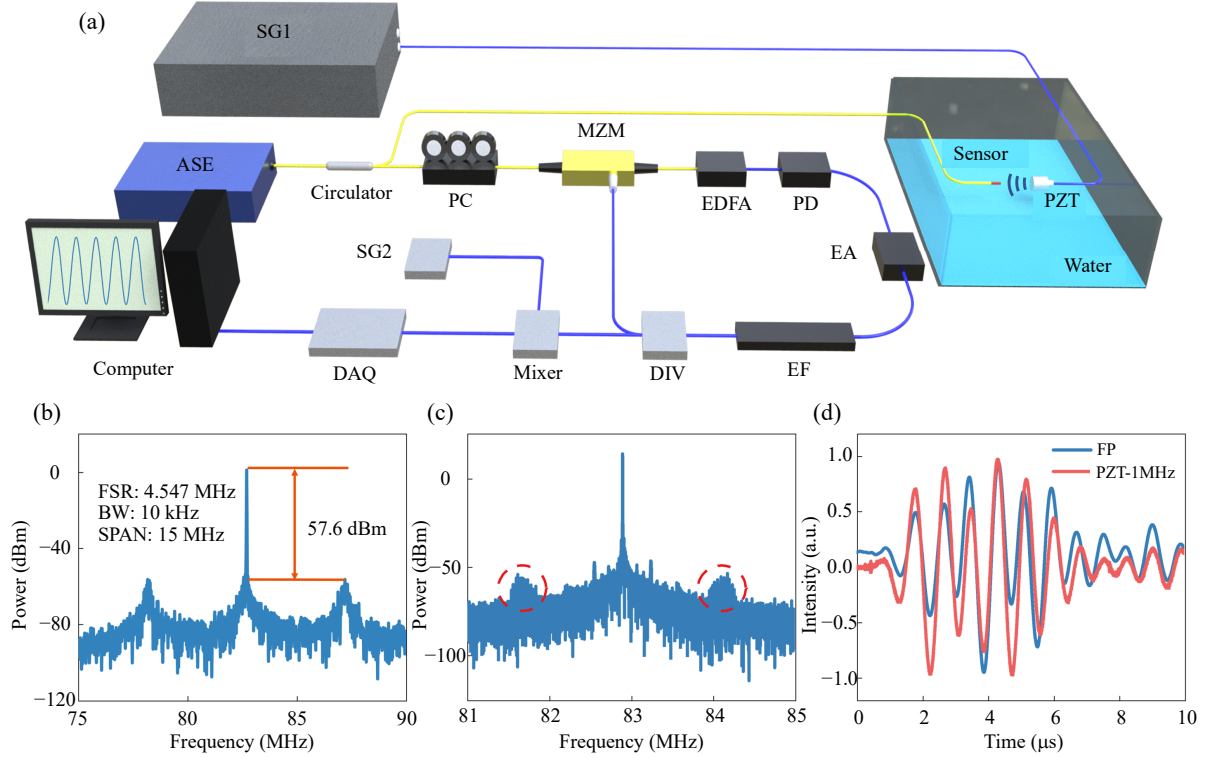


Fig. 2 Experimental setup and system performance: (a) the schematic diagram of the sensing system, (b) the electrical spectrum of the generated 82.897 MHz signal, (c) the RF spectrum of the OEO output under ultrasonic modulation, and (d) the demodulated waveform in comparison with the reference signal.

In an OEO, the FSR_{OEO} determines the spacing between cavity modes. A sufficiently large FSR_{OEO} enables the principal mode to occupy a distinct frequency band, thereby reducing interference from other modes. This is especially important when the high-frequency ultrasound is modulated, as it may cause interference between adjacent modes. Therefore, to effectively distinguish ultrasound-modulated information from interference from fixed cavity modes, it is essential to maximize the FSR_{OEO} . The FSR_{OEO} of the OEO can be expressed as [35]

$$\text{FSR}_{\text{OEO}} = \frac{1}{\tau} \quad (2)$$

where τ is the total time delay of the OEO loop.

Given that the FSR_{OEO} of the OEO is predominantly determined by the loop delay, efforts were made in the system design to minimize the OEO loop delay to achieve a larger FSR. Figure 2(b) illustrates the electrical spectrum of the OEO oscillation signal. The original oscillation frequency of the OEO was 5.645 GHz, which was down-converted to 82.897 MHz to relax the hardware requirements for the DAQ. An FSR_{OEO} of 4.547 MHz and a high sideband suppression ratio (SSR) of up to 57.6 dBm were achieved. At a 10 kHz frequency offset, the OEO's phase noise was measured at -80.627 dBc/Hz. This spectral purity ensured that the microwave carrier's amplitude served as a stable

and low-noise platform for encoding ultrasonic information.

To evaluate the practical demodulation performance of the system for ultrasonic signals, a comparative platform was constructed using a pair of ultrasonic transducers (1 MHz; A303S, Olympus, Japan). One transducer emitted ultrasound waves to excite the FP sensor. At the same time, the other simultaneously received direct acoustic signals as a reference for comparison with the ultrasound signals demodulated by the FP sensor. Figure 2(c) shows the RF spectrum at the output of the OEO loop for the FP sensor, where clearly observable symmetric sidebands (highlighted by red circles) induced by ultrasonic modulation confirmed the effective modulation of the FP cavity length by the ultrasound. Furthermore, by applying an I/Q demodulation algorithm to extract the sideband intensity, accurate reconstruction of the ultrasonic waveform was achieved, as shown in Fig. 2(d). The demodulated waveform from the OEO system closely matched the reference signal from the commercial transducer, validating the feasibility of the proposed system for high-fidelity ultrasonic demodulation in the 1 MHz frequency band.

4. Sensor characterization and imaging

A series of experiments were conducted to validate the performance of the proposed FP ultrasonic sensing system. As schematically illustrated in Fig. 2(a), both the sensor and a calibrated reference ultrasonic transducer were immersed in a water tank. The transducer was driven by a signal generator (DG1022U, SG1) to generate acoustic waves. For the comparative assessment of demodulation schemes, the performance of the proposed OEO method was benchmarked against conventional sideband filtering intensity demodulation. Different pulse voltages were applied via the signal generator to drive the 1 MHz ultrasonic transducer. Figures 3(a) and 3(b) quantitatively compare the two demodulation schemes, showing that the OEO method achieved

the sensitivity of 5.099 mV/V_{pp}, compared to 3.199 mV/V_{pp} to the conventional quadrature-point locking method. This result confirmed that the proposed OEO demodulation scheme attained the sensitivity comparable to that of the traditional intensity-based method, thereby validating its feasibility.

Furthermore, experiments were conducted to evaluate the temperature immunity of the demodulation methods. Under a fixed driving voltage, a stable 1 MHz ultrasonic signal was generated to excite the sensor, with its aqueous environment temperature controlled by a water bath. As shown in Fig. 3(c), the sensor's reflection spectrum exhibits a red shift with increasing temperature. The OEO demodulation result [the red curve, Fig. 3(d)] showed only minor fluctuations, with a maximum variation of 3.34 mV. In contrast, the conventional sideband-filtering method, represented by the blue curve in Fig. 3(d), produced a maximum variation of 25.79 mV. For the latter, a tunable narrow-linewidth laser was stabilized at the spectral quadrature point at 30 °C, yet its output still exhibited significant fluctuations with the temperature drift. These results confirmed the OEO method's superior resistance to the temperature interference.

To further characterize the sensor performance, its response to continuous-wave ultrasound was evaluated. A 1 MHz sinusoidal acoustic signal was applied, and the sensor output was recorded under various pressure levels. As shown in Fig. 4(a), the time-domain waveforms exhibited the consistent response under different ultrasonic pressure. The peak-to-peak amplitudes were averaged and plotted against the applied acoustic pressure, demonstrating a highly linear relationship ($R^2=0.995$) in Fig. 4(b). From the linear fit, the pressure sensitivity was determined to be 3.089 mV/kPa. Based on the measured noise level of 0.52 mV, the noise-equivalent pressure (NEP) was estimated as 168 Pa, confirming the sensor's high sensitivity and low detection limit.

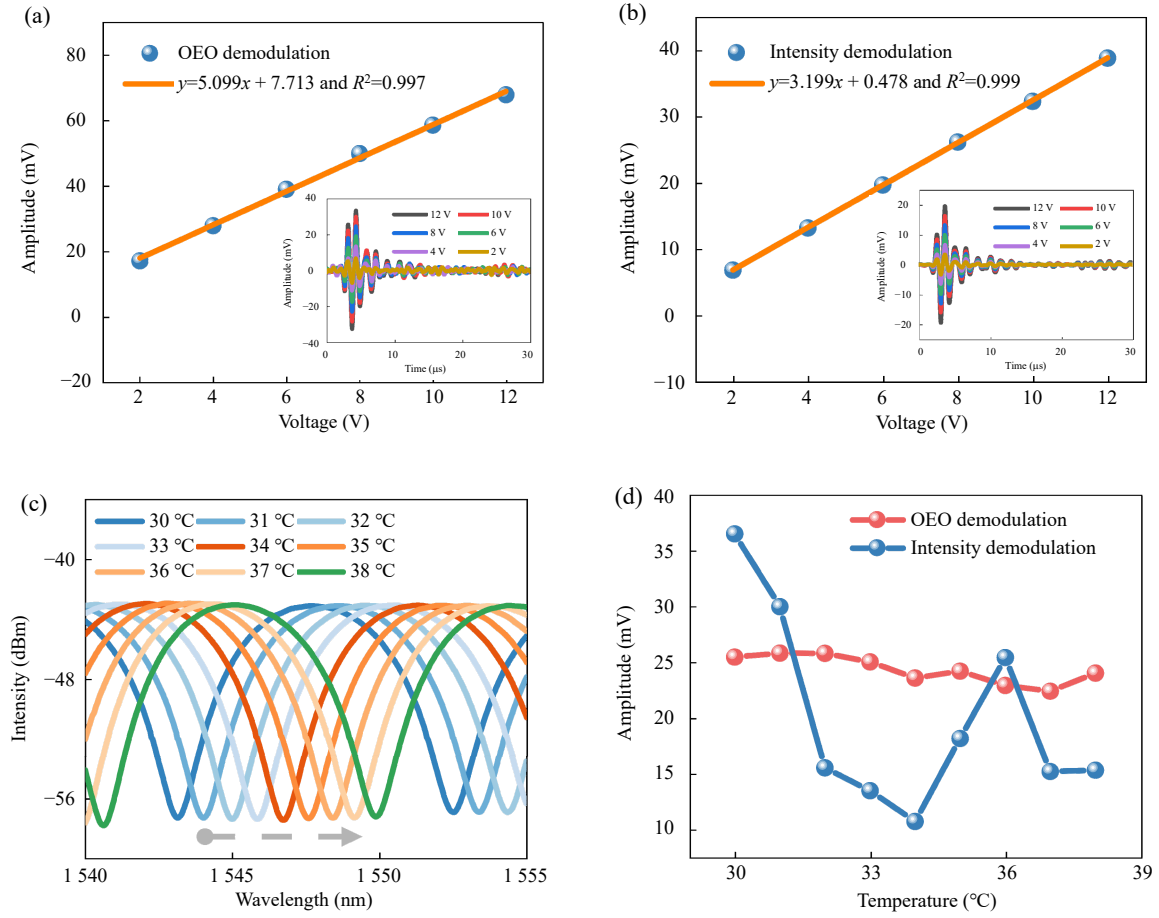


Fig. 3 Performance comparison of demodulation schemes: (a) the signal demodulated by the proposed OEO method, (b) the signal demodulated by the conventional sideband filtering method, (c) the reflection spectrum under the varying temperature, and (d) the demodulated signal stability under temperature variations.

The sensor's frequency response and directivity were further characterized. A broadband ultrasonic signal was generated by irradiating a black tape with a pulsed laser (the wavelength: 532 nm; pulse energy: 8 μ J). The acquired pulse response is depicted in Fig. 4(c). The fast Fourier transform (FFT) analysis of this signal revealed a central frequency of 1.753 MHz, which was close to the simulated resonant frequency, along with a bandwidth of 2.881 MHz, defined as the frequency range where the magnitude dropped to 20% of its peak value. Furthermore, the angular dependence of the sensor was investigated, as shown in Fig. 4(d). The results indicated a wide angular response range exceeding 180 $^{\circ}$, making it well-suited for

applications, such as photoacoustic tomography where a wide detection angle can significantly enhance the imaging quality and field of view.

To evaluate the practical imaging performance of the proposed sensing and demodulation system, an underwater ultrasound scanning experiment was conducted using the setup shown in Fig. 5(a). A 1 MHz ultrasonic transducer and the fabricated FP sensor were placed side-by-side in a water tank. A 3D-printed resin step target with a convex profile – having a nominal length of 12 mm and a step height of 5 mm – was scanned along its X-direction using a two-axis translation stage with a step size of 20 μ m. Inside the target, a 1 mm diameter copper wire was

embedded as a highly reflective internal feature (the inset of Fig. 5(c)). Figure 5(b) displays a typical demodulated I/Q signal after real-time processing, where clear echoes from the front and rear surfaces of the step target can be identified. Figure 5(c) presents the B-scan image obtained after

maximum-value extraction, data interpolation, and the Gaussian filtering, revealing distinct intensity variations and gradient distributions (marked in pink). A strong internal reflection from the embedded copper wire was clearly observed near the image centers.

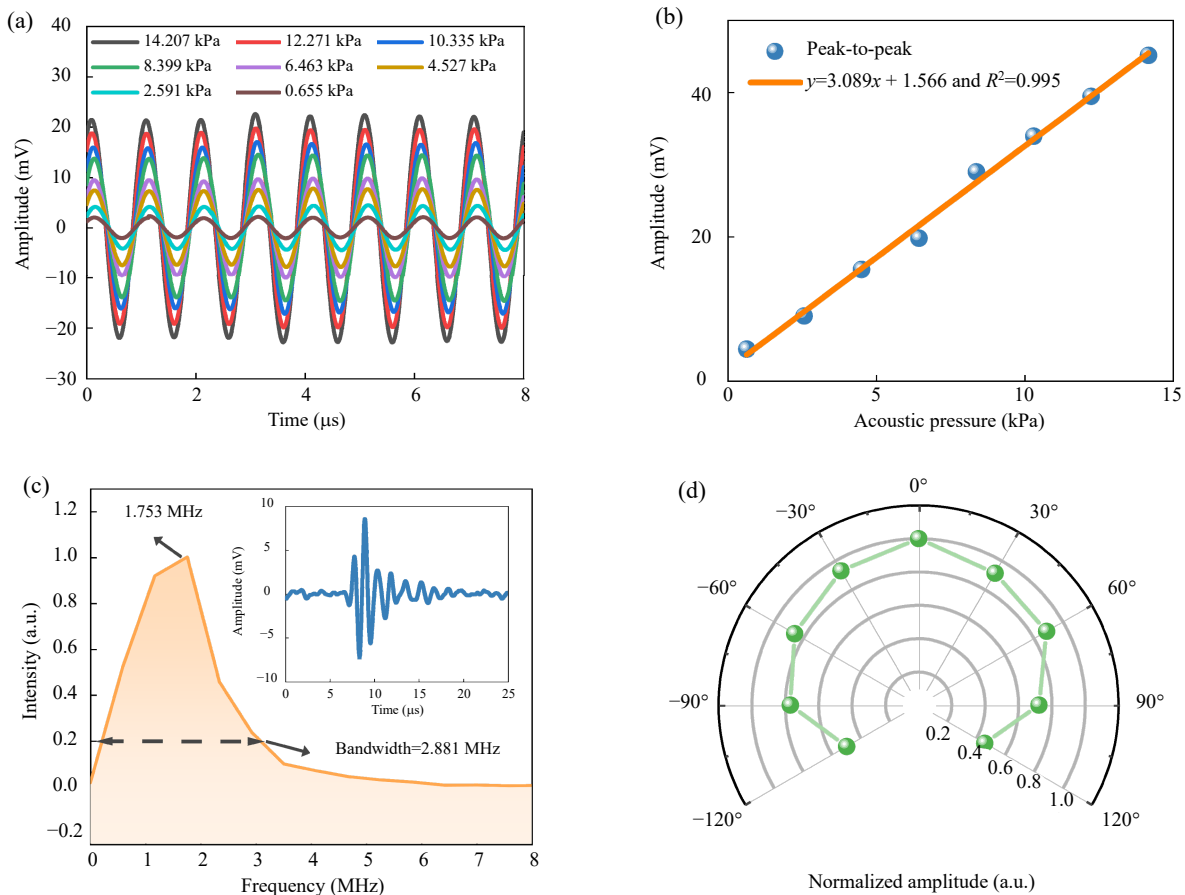


Fig. 4 Sensor response to acoustic pressure: (a) time-domain waveforms under various pressure levels and (b) the peak-to-peak voltage as a function of applied pressure with a linear fit. The sensor bandwidth and directivity: (c) the pulse response and corresponding FFT spectrum and (d) the normalized amplitude versus the incident angle.

The surface profile of the scanned target was successfully reconstructed through boundary-smoothing analysis of the depth-resolved signals shown in Fig. 5(c), with the result presented in Fig. 5(d). The obtained imaging length was measured as 11.445 mm, which aligned closely with the nominal value of 12 mm; observed minor deviations were primarily attributed to the positioning tolerance of the stepper motor and the performance of the boundary-extraction algorithm.

Moreover, the measured step height of 4.996 mm demonstrated excellent agreement with its designed dimension. Notably, a strong depth-resolved signal from the embedded copper wire was clearly observed in the B-scan image, highlighting the system's capability to resolve internal reflective features. These outcomes confirmed the high reliability, measurement accuracy, and robust demodulation stability of the proposed system in practical imaging scenarios.

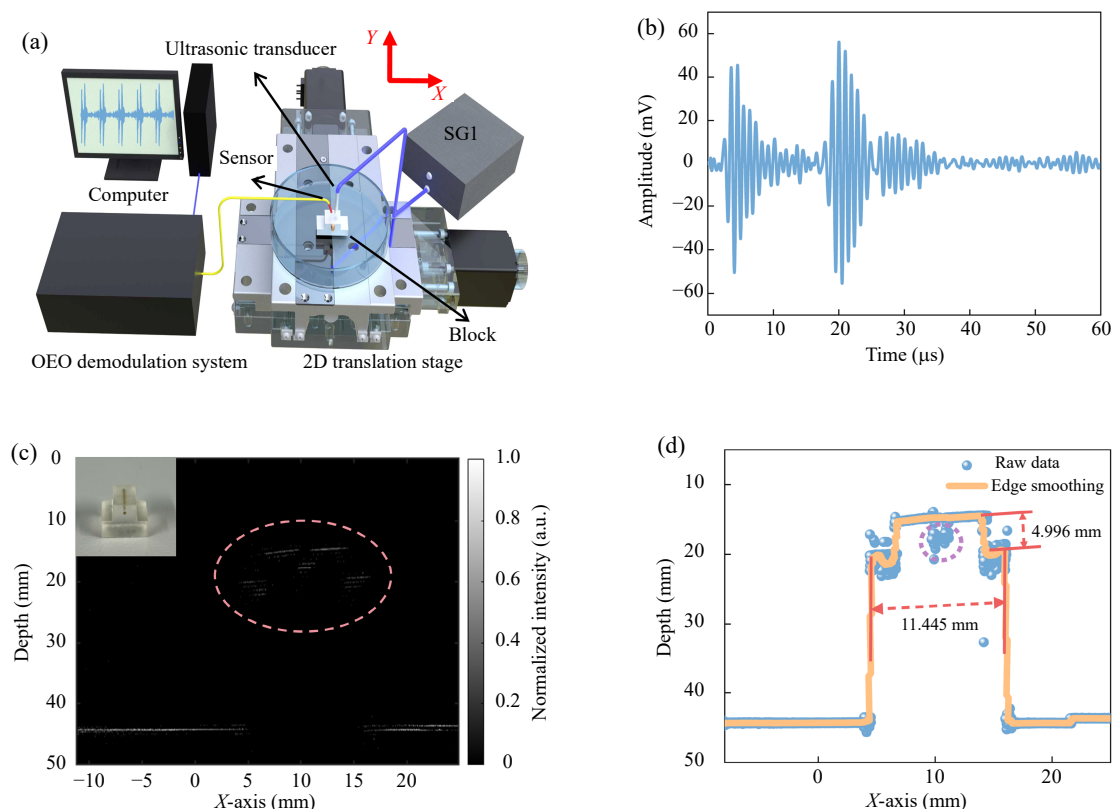


Fig. 5 Experimental results of ultrasound imaging: (a) the schematic diagram of the experimental setup, (b) a typical demodulated ultrasonic pulse signal acquired in real time, (c) the B-scan image of the step-shaped target showing internal and surface reflections, and (d) the reconstructed surface profile of the target obtained through boundary-smoothing analysis of depth-resolved signals in (c).

5. Conclusions

In summary, this paper presented and experimentally validated a highly sensitive FP fiber-optic ultrasound sensing system based on an OEO. By integrating a fiber-tip microcavity fabricated via two-photon polymerization with a low-phase-noise OEO, the system enabled efficient modulation and demodulation of ultrasonic signals on a microwave carrier. Experimental results show that the sensor achieved the sensitivity of 3.089 mV/kPa at 1 MHz, noise-equivalent pressure of 168 Pa, a bandwidth of 2.881 MHz, and an ultra-wide directivity exceeding 180°. Unlike conventional intensity-demodulation approaches, the proposed OEO-based scheme employed a broadband optical source and operated without active quadrature-point stabilization. This architecture not only maintained competitive sensitivity but also significantly suppressed the temperature-induced

drift inherent in TPP-fabricated polymer sensors, thereby greatly enhancing operational robustness under varying environmental conditions. Furthermore, underwater ultrasound scanning experiments successfully reconstructed the surface profile of a 3D-printed resin step target with a convex geometry. The measured length (11.445 mm) and step height (4.996 mm) showed excellent agreement with their nominal dimensions, confirming the system's feasibility and reliability in practical imaging applications. These findings underscore the potential of the proposed system for high-precision acoustic sensing in fields, such as structural health monitoring, photoacoustic imaging, and underwater acoustic holography.

Data availability

All data needed to support the conclusions in the paper are presented in the article and/or the

Supplementary files. Additional data related to this paper may be requested from the corresponding author upon request.

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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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Use of AI Statement None.

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