

Article

Polarization-Multiplexed Chaotic LiDAR Based on a VCSEL with Delayed Orthogonal Feedback

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Abstract

Light detection and ranging (LiDAR) systems are pivotal for precise distance and velocity measurement, yet widespread deployment requires solutions that balance their performance, robustness, and simplicity. Here, we propose a novel chaotic LiDAR system based on a semiconductor vertical-cavity surface-emitting laser (VCSEL) with delayed orthogonal polarization feedback. By exploiting the intrinsic competition between the transverse electric (TE) and transverse magnetic (TM) modes, the system generates polarization-multiplexed dynamics: a chaotic TM mode serves as the reference, while a feedback-modulated TE mode probes the target. This all-in-one source eliminates the need for external optical modulators or complex coherent detection. The system's dynamics are finely tunable via a half-wave ($\lambda/2$) plate in the feedback loop and the laser injection current, enabling real-time optimization of the cross-correlation signal-to-noise ratio. Experimental results demonstrate precise linear ranging with a resolution of approximately 1.2 cm. Furthermore, the system exhibits strong inherent resistance to external optical interference, maintaining accurate ranging even in the presence of a secondary laser source. This compact, tunable, and interference-resilient platform offers a promising pathway toward low-cost, high-performance LiDAR for applications in autonomous navigation, robotics, and industrial metrology.

Keywords: chaotic LiDAR; VCSEL; polarization dynamics; optical ranging; delayed feedback



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1. Introduction

As an advanced environmental perception technology, LiDAR plays a significant role in various fields [1], such as autonomous driving [2], robotics [3], and airborne remote sensing [4]. Conventional LiDAR systems often employ pulsed lasers as the light source, determining target distance through the time-of-flight (TOF) of back-scattered optical pulses [5,6]. This method is well-suited for long-range applications but requires careful management of high peak powers to comply with laser safety standards [7]. In contrast, frequency-modulated or amplitude-modulated continuous-wave (FMCW/AMCW) LiDAR systems emit a continuously modulated laser beam and derive distance information from the frequency difference between the transmitted and reflected signals [8,9]. While they enable high precision and sensitivity, such systems demand ultra-narrow-linewidth tunable lasers and stable coherent detection optics, increasing system complexity and cost [10,11].

Recently, in addition to single-photon LiDAR [12,13], random-modulated continuous-wave (RMCW) LiDAR has emerged as an alternative, modulating laser intensity with a pseudo-random binary sequence to achieve noise-like coding [14]. This approach retains the time-domain measurement principle of pulsed LiDAR while offering improved resistance to interference from other sources [15]. However, external modulation components introduce additional hardware complexity. Another promising direction is chaotic LiDAR, which utilizes broadband chaotic waveforms generated directly from semiconductor lasers [16]. By correlating the reflected chaotic signal with a time-delayed reference, centimeter-level ranging resolution can be achieved without external modulation, offering a simpler and more efficient system architecture [17].

In this work, we demonstrate a high-performance chaotic LiDAR system based on the orthogonal polarization dynamics of a semiconductor VCSEL. VCSELs offer advantages including compact size, low threshold current, low cost, and stable operation, making them highly suitable for practical ranging applications [18,19]. By introducing delayed orthogonal feedback via an external ring cavity and inserting a half-wave plate to fine-tune the coupling between TE and TM modes, we selectively generate amplified random spikes in the TM mode and fast oscillations in the TE mode. The TM mode serves as a reference, while the TE mode is directed toward the target. The reflected echo is anti-correlated with the reference signal, enabling precise time-of-flight extraction with strong anti-interference capability. Our system achieves a linear ranging response and a centimeter resolution, with further performance tuning possible through adjustment of the half-wave plate angle or laser drive current. Thus, these features collectively enable a robust, tunable, and compact chaotic LiDAR platform, promising enhanced performance in applications requiring high resolution, interference resistance, and system simplicity.

2. Experimental Setup

The schematic diagram of the LiDAR ranging system is illustrated in Figure 1. The system consists of a transmitter module and a receiver module. In the transmitter, a single-mode semiconductor VCSEL (Thorlabs L850VH1, 850 nm, Shanghai, China) serves as the light source, with an external ring cavity providing delayed optical feedback. The VCSEL is temperature-stabilized at 25° using a temperature controller (Thorlabs TED200C, Shanghai, China) and driven by a low-noise current source (Thorlabs LDC205C, Shanghai, China).

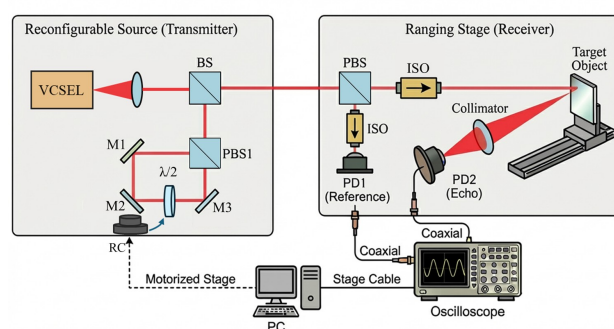


Figure 1. The setup is divided into two parts: the transceiver module (**left box**) and the receiving stage (**right box**). In the transceiver module: VCSEL, vertical-cavity surface-emitting laser; BS, beam splitter; PBS1, polarizing beam splitter; M1, M2, M3, mirrors; $\lambda/2$, half-wave plate with rotation controller (RC) connected to a personal computer (PC). The PC controls the wave plate angle independently of the target signal. In the receiving stage: PBS separates the TE and TM modes; the TM mode is detected by PD1 as the reference, while the TE mode passes through an optical isolator (ISO) and is directed toward the target. The reflected echo from the target is collected and detected by PD2. Both PD1 and PD2 are connected to the PC for crosscorrelation analysis.

Within the transmitter module, the collimated laser output first passes through a 50:50 beam splitter (BS, BS2555-T3M, JCOPTIX, Nanjing, China), splitting the beam into two branches. The first branch enters the ring cavity, which is constructed using a polarizing beam splitter (PBS1, PBS25-2, JCOPTIX, Nanjing, China) and three high-reflection mirrors (M1, M2, and M3; OME1-R3-P6, JCOPTIXm Nanjing, China). Within the ring cavity, a half-wave ($\lambda/2$, TWP20H-850P, JCOPTIX, Nanjing, China) plate is inserted to manipulate the polarizations states. The rotation of this plate is controlled via a rotator controller (RC) interfaced with a computer, enabling precise angular adjustment. As light traverses PBS1, the TE and TM polarization modes are separated and propagate in clockwise and counter-clockwise directions, respectively. Consequently, the coupling between these orthogonal modes is dynamically controlled via the angle of the $\lambda/2$ plate [20,21].

The second optical branch is directed to the receiver stage. After passing through a second polarizing beam splitter (PBS), the TM mode is detected using a DC-coupled amplified photodetector (PD1, KY-APRM-10G, KEYANG, Beijing, China), serving as the reference signal. The TE mode is transmitted toward a target, and the reflected echo is collected and detected by a second photodetector (PD2, KY-APRM-10G, KEYANG, Beijing, China). Both signals are recorded simultaneously using a high-bandwidth digital oscilloscope (Tektronix DSA72004, 20 GHz bandwidth, Tektronix, Beaverton, OR, USA). Subsequent crosscorrelation analysis is performed computationally to extract the time-of-flight and corresponding target distance. By utilizing the orthogonal polarization states of the VCSEL, the system inherently separates the reference and probe signals without additional optical modulators or complex filtering. This method can minimize crosstalk, reduce optical loss, and simplify the detection path.

Importantly, the rotation of the $\lambda/2$ plate is adjusted solely by the computer via the rotator controller and does not rely on any feedback from the target echo, eliminating any potential misunderstanding about the system's control architecture.

3. Results and Discussion

The static and dynamic properties of the vertical-cavity surface-emitting laser (VCSEL) under both free-running and feedback conditions are essential for understanding its operation as a chaotic LiDAR source. Figure 2a presents the light-current (L-I) characteristics for the total emission (black curve) and the individual transverse electric (TE, red) and transverse magnetic (TM, blue) polarization modes. The TE mode is the dominant lasing polarization, exhibiting a threshold current identical to that of the total output (~ 1.6 mA). In contrast, the TM mode remains strongly suppressed at currents below approximately 5.20 mA, operating primarily in the regime of amplified spontaneous emission (ASE) [22]. This polarization selectivity is intrinsic to the VCSEL structure and establishes the TE mode as the primary carrier of coherent optical power, while the TM mode provides a sub-threshold, noise-like signal component.

The typical dynamical properties of the free-running laser are examined in Figure 2b and c, which display the radio-frequency (RF) spectra of the TE and TM modes at a pump current of $J = 1.64$ mA. The RF spectra are obtained by performing a Fourier transform on the temporal signals recorded by the oscilloscope. Accordingly, the vertical axis is plotted in arbitrary units (arb. units) and is only for relative spectral comparison. The TE-mode spectrum (Figure 2b) features a pronounced relaxation oscillation peak centered at approximately 2.7 GHz, indicative of its coherent, above-threshold dynamics. Conversely, the TM-mode spectrum (Figure 2c) is dominated by low-frequency broadband components, consistent with its ASE-driven, incoherent nature below the threshold [23].

Introducing delayed orthogonal feedback via the external ring cavity dramatically tailors the laser dynamics. The time trace of the TE mode (Figure 2d) exhibits fast, irregular

oscillations, and its corresponding RF spectrum (Figure 2e) shows broadening and intensity enhancement compared to the free-running case. This indicates the degradation of coherence and chaotic modulation induced by the reinjected field. The autocorrelation function of the TE intensity (Figure 2f) exhibits a sharp central peak accompanied by symmetric sidelobes, a signature of delayed feedback that imposes a periodic memory on the otherwise stochastic waveform [24,25].

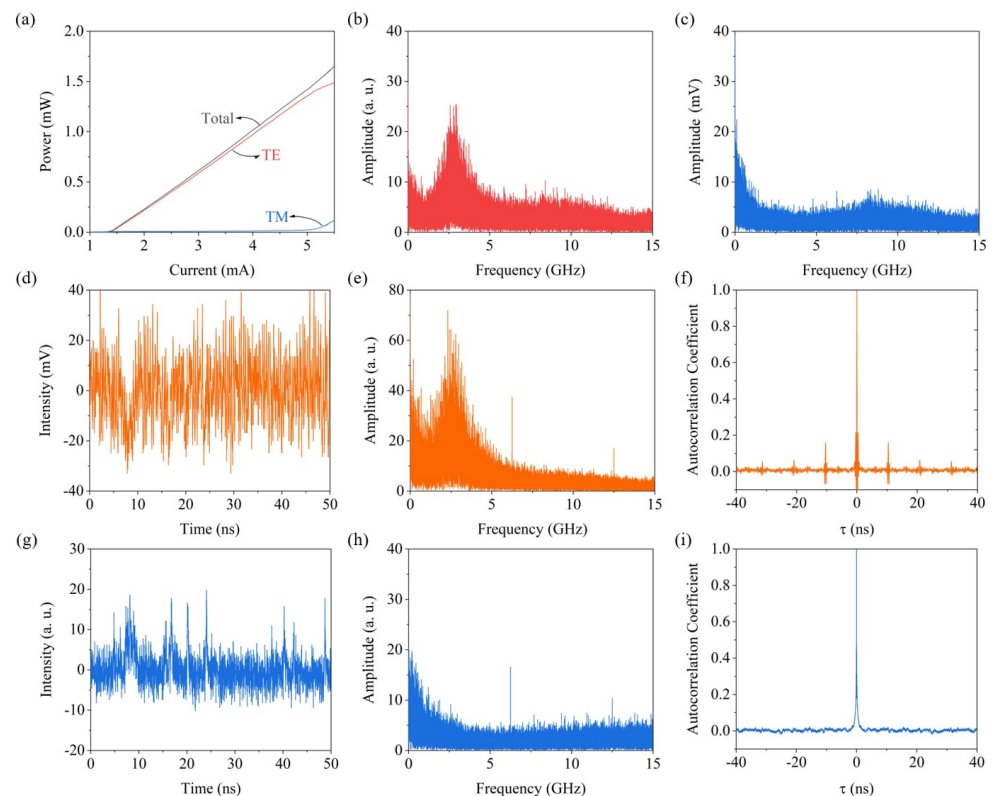


Figure 2. Static and dynamic characterization of the VCSEL under free-running and delayed orthogonal feedback conditions: (a) light–current (L–I) curves for the total output (black) and the individual TE (red) and TM (blue) polarization modes; (b,c) radio-frequency (RF) spectra of the (b) TE and (c) TM modes for the free-running laser at $J = 1.64$ mA. (d–f) Dynamics of the TE mode under orthogonal feedback: (d) temporal trace, (e) corresponding RF spectrum and (f) autocorrelation function. (g–i) Dynamics of the TM mode under the same feedback: (g) time series, (h) RF spectrum, and (i) autocorrelation function.

Simultaneously, the TM mode evolves into a train of random, intensity-varying spikes (Figure 2g). Its RF spectrum (Figure 2h) remains concentrated at low frequencies, confirming that its dynamics are not governed by relaxation oscillations but by amplified stochastic fluctuations. The autocorrelation of the TM mode (Figure 2i) displays a rapidly decaying, featureless profile characteristic of broadband chaos, without distinct peaks corresponding to external cavity modes. This confirms that the TM mode operates as an aperiodic, noise-like reference signal.

Figure 3a presents the crosscorrelation function (CCF) between the TE and TM polarization modes under delayed orthogonal feedback. A pronounced inverted (anti-correlation) peak is observed at zero time delay ($\tau = 0$), signifying a negative correlation between the two orthogonal polarization states. This anti-correlation is due to the competitive dynamics induced by the polarization-selective feedback loop, wherein intensity increases in one mode correspond to decreases in the other, corresponding to one typical property of non-linear mode coupling in the laser cavity [20,26]. In addition to the central anti-correlation peak, symmetric sidelobes (wings) are observed, which are a direct signature of the de-

layered optical feedback from the external ring cavity. These recurring correlation features correspond to the round-trip time of the feedback loop and confirm the periodic reinjection of the orthogonal polarization components into the laser cavity.

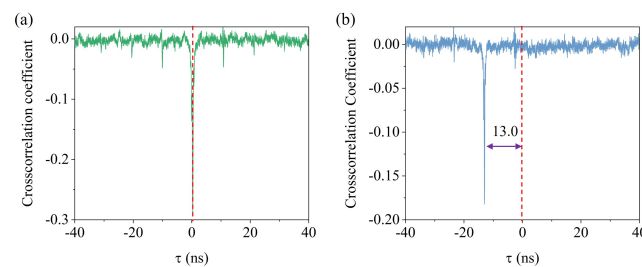


Figure 3. Crosscorrelation characterization of the chaotic LiDAR system. (a) CCF between the TE and TM polarization modes under orthogonal feedback. (b) CCF between the TE and TM polarization modes when a target echo is detected.

The anti-correlation originates from the nonlinear gain competition and carrier dynamics within the VCSEL's active region [27]. Both polarization modes extract gain from the same carrier reservoir, and the VCSEL's intrinsic birefringence leads to a frequency splitting between them, which governs the mode-beating dynamics and the feedback-induced coupling. Under delayed orthogonal feedback, the selectively amplified TE mode depletes the local carrier density via spatial hole burning [28], transiently suppressing the orthogonal TM mode. This nonlinear competition is well captured by the spin-flip model [26,29]

The external polarization coupling described above can be quantified by using Jones calculus. In the external ring cavity, PBS1 separates the TE and TM modes into counter-propagating paths. The half-wave plate, with its fast axis oriented at an angle θ relative to the TE axis, introduces a phase retardation of π between the orthogonal components, as described by the Jones matrix [30]:

$$J_{\text{HWP}}(\theta) = \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ \sin 2\theta & -\cos 2\theta \end{pmatrix} \quad (1)$$

Consequently, the feedback-coupling matrix that relates the reinjected fields to the delayed fields is

$$\mathbf{F}(\theta) = \begin{pmatrix} \eta_{TE} \cos 2\theta & \eta_{TM} \sin 2\theta \\ \eta_{TE} \sin 2\theta & -\eta_{TM} \cos 2\theta \end{pmatrix} \quad (2)$$

where η_{TE} and η_{TM} denote the feedback strengths for the respective polarization channels. This matrix formulation shows that the off-diagonal (cross-polarization) terms $\propto \sin 2\theta$ govern the TE-TM mixing, while the diagonal (self-feedback) terms $\propto \cos 2\theta$ control the polarization-preserving reinjection. Therefore, the angle θ directly sets the balance between orthogonal and parallel feedback, which dictates the anti-correlation amplitude observed in Figures 4 and 5 and provides a theoretical foundation for the tunability of the system.

When putting a target into the optical path, the TE-mode echo signal reflected from the target is captured by the detector. The resulting CCF shifts distinctly from $\tau = 0$ (Figure 3b). The observed time shift of approximately 13 ns corresponds to the round-trip propagation delay between the detector and the target. Using the relation $d = c \cdot \Delta\tau/2$ (where c is the speed of light), this delay translates to a target distance of ~ 1.95 m. This clear temporal displacement of the anti-correlation peak demonstrates the ranging capability of the system.

The sharpness of the correlation peak and its well-defined shifting under target reflection collectively suggest excellent time-domain resolution and low timing jitter, which are significant for precise distance measurement. Furthermore, the use of an inherently anti-correlated dual-polarization source enhances robustness against common-mode noise

and external interference. Therefore, the result validates the proposed chaotic LiDAR scheme, without the need for high-speed modulation or coherent detection.

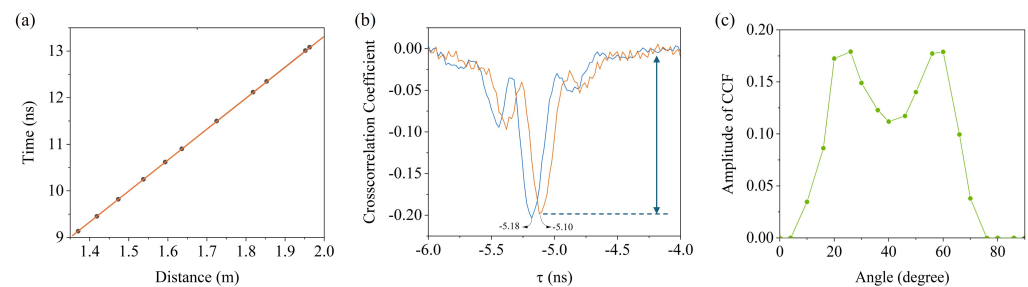


Figure 4. Linearity, resolution, and tunability of the chaotic LiDAR system. (a) Measured time shift of the anti-correlation peak as a function of target distance; (b) fine displacement measurements; (c) amplitude of the crosscorrelation anti-correlation peak as a function of the $\lambda/2$ -plate angle.

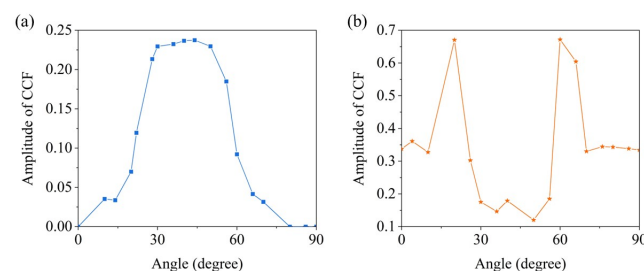


Figure 5. Tunable operating regimes of the chaotic LiDAR system via current and polarization control: (a) $J = 2.10$ mA; (b) $J = 5.76$ mA.

The chaotic dynamics generated through orthogonal feedback share distinct parallels with recent developments in mutual optical injection architectures. For example, Tang et al. [31] experimentally show that two mutually injection-locked semiconductor lasers with a long delay line can generate wide-bandwidth chaotic signals, where the dynamics are controlled by frequency detuning and coupling strength. While such mutual injection systems offer tunable chaos, they need precise alignment of two discrete lasers and complex optoelectronic feedback loops. In contrast, our proposed architecture achieves a comparable high-entropy, wide-bandwidth chaotic carrier by exploiting the intrinsic polarization dichotomy (birefringence) of a single VCSEL, thereby significantly reducing hardware complexity and eliminating the need for a second laser source.

In Table 1, we show the advantages of the proposed platform through comparison of conventional LiDAR architectures. While FMCW systems give millimeter precision, they require ultra-narrow-linewidth tunable lasers and complex coherent detection setups. In contrast, our system shows comparable common-mode noise suppression and interference resistance by using a single, low-cost VCSEL and direct crosscorrelation, effectively bridging the gap between hardware simplicity and high-fidelity detection.

Table 1. Comparison of key indicators for different LiDAR architectures.

Architecture	Source Complexity	Detection Scheme	External Modulator Required	Interference Resistance	Typical Resolution	Cost Implication
Pulsed ToF	Low	Threshold	No	Medium	Centimeter	Low
FMCW	High	Coherent	No	High	Millimeter	High
Traditional RMCW	Medium	Correlation	Yes	High	Centimeter	Medium
Proposed Chaotic	Low	Correlation	No	High	Centimeter	Low

To comprehensively evaluate the ranging performance of the system, we quantified the relationship between the temporal shift of the anti-correlation peak and the physical target

distance. Figure 4a plots the measured time shift $\Delta\tau$ as a function of the distance between the target and the detector. The discrete points represent experimental measurements at each distance, and the orange solid line is the linear fit ($\Delta\tau = 6.67 \text{ ns/m} \cdot d + 0.02 \text{ ns}$, $R^2 = 0.998$), confirming that $\Delta\tau$ scales directly with the round-trip propagation delay. This linear response validates the fundamental time-of-flight operating principle and ensures reliable distance decoding without complex calibration.

We further characterized the practical resolution of the system by displacing the target in fine increments. As shown in Figure 4b, the minimum detectable step change in distance is on the order of centimeters, which is consistent with the temporal width of the crosscorrelation peak and the effective bandwidth of the chaotic waveform. We note that since the minimum detectable step change results from an intensity correlation calculation, it is independent of the target distance, even beyond the laser coherence length. This resolution is competitive with conventional chaotic LiDAR systems and can be attributed to the broad, noise-like spectrum generated under delayed orthogonal feedback.

The ranging resolution is governed by the effective bandwidth of chaotic signal B and the sampling rate of the oscilloscope f_s . The fundamental resolution limit is given by

$$\Delta R = \max\left(\frac{c}{2B}, \frac{c}{2f_s}\right) \quad (3)$$

In our experimental setup, the VCSEL's relaxation oscillation frequency, $f_{RO} \approx 2.7 \text{ GHz}$, limits B to approximately 3–4 GHz, giving an optical-bandwidth-limited resolution of about 4–5 cm. The measured resolution of $\sim 1.2 \text{ cm}$ is better than this estimate because the chaotic spectrum is not flat; higher-frequency components contribute to a sharper correlation peak. The oscilloscope (Tektronix DSA72004) has a sampling rate of 50 GS/s, corresponding to a sampling interval of 20 ps and a single-sample distance resolution of 3 mm. Therefore, the oscilloscope is not the limiting factor in our current demonstration.

To push the resolution toward the millimeter scale, the chaotic bandwidth must be expanded beyond 10 GHz. By using the current experimental setup, this can be achieved by (i) increasing the bias current to elevate the relaxation oscillation frequency (at the same time, careful thermal management is required) and (ii) employing VCSELs with larger birefringence through integrated surface gratings or anisotropic gain media and then increasing the polarization mode splitting and the associated chaos bandwidth. In such a future system, maintaining a digitizer with a sampling rate of at least 50 GS/s (or higher, e.g., 100 GS/s) would be necessary to fully exploit the increased bandwidth.

One distinctive feature of our setup is the ability to dynamically tune the system's sensitivity via the $\lambda/2$ -plate within the feedback loop. As shown in Figure 4c, rotating the wave plate modifies the polarization coupling between the TE and TM modes, thereby adjusting the amplitude of the anti-correlation peak. This adjustment directly influences the signal-to-noise ratio (SNR) of the correlation signal, enabling real-time optimization of detection sensitivity and ranging accuracy for different operational scenarios. Thus, the $\lambda/2$ -plate serves as an in-line gain control that tailors the chaotic dynamics without altering the laser drive conditions or external feedback length, enabling the practicality of our system for robust, reconfigurable optical ranging applications.

While a mechanical rotator can provide precise angular control with a certain speed, it is primarily suitable for static optimization of the system's operating point, rather than real-time adaptive tracking. For use cases demanding fast dynamic reconfiguration, such as live compensation of environmental drift or time-varying echo loss, a liquid-crystal variable retarder (LCVR) can substitute for the mechanical half-wave plate, affording millisecond-scale response speeds. This hardware substitution would permit closed-loop tuning of the

anti-correlation amplitude throughout continuous long-term operation, thereby further boosting the system's environmental adaptability.

Another distinct advantage is that our chaotic LiDAR system exhibits a broad operational tunability, enabling performance optimization across varying conditions. Figure 5a presents this capability by plotting the amplitude of the anti-correlation peak as a function of the $\lambda/2$ -plate angle (θ) for two distinct pump currents. At a pump current of $J = 2.10$ mA, the amplitude increases with θ , reaches a plateau of maximum values within the range $30^\circ \leq \theta \leq 50^\circ$, and subsequently declines. This indicates an optimal polarization-coupling regime where the interaction between the TE and TM modes gives the highest signal-to-noise ratio (SNR) for correlation-based ranging.

When the pump current is elevated to $J = 5.76$ mA, the system enters a different dynamical state. Here, larger anti-correlation amplitudes (exceeding 0.3) are sustained within two distinct angular regions: $\theta \leq 26^\circ$ and $\theta \geq 60^\circ$. This bimodal response demonstrates that the system's operating point can be selectively tuned not only via the $\lambda/2$ -plate but also through the injected current, effectively broadening the parameter space for achieving high-performance detection.

Finally, we evaluated the anti-interference capability of our LiDAR system, a critical metric for operation in spectrally crowded environments. To simulate realistic optical crosstalk, an intentional interference signal was generated using a separate 850 nm semiconductor laser (Thorlabs L850P030, Shanghai, China) operating at a drive current of $J = 73$ mA (far above threshold). To avoid saturating or damaging the photodetector, only a small fraction (around 10%) of the interference power is coupled into the detection path via a beam splitter. The temporal trace of this interfering source, shown in Figure 6a, exhibits fast oscillations, and distinct changes become visible when the interference signal is blocked. Its corresponding RF spectrum (Figure 6b) is dominated by a broad peak centered near 10 GHz, characteristic of the relaxation oscillations and intrinsic noise of the free-running laser.

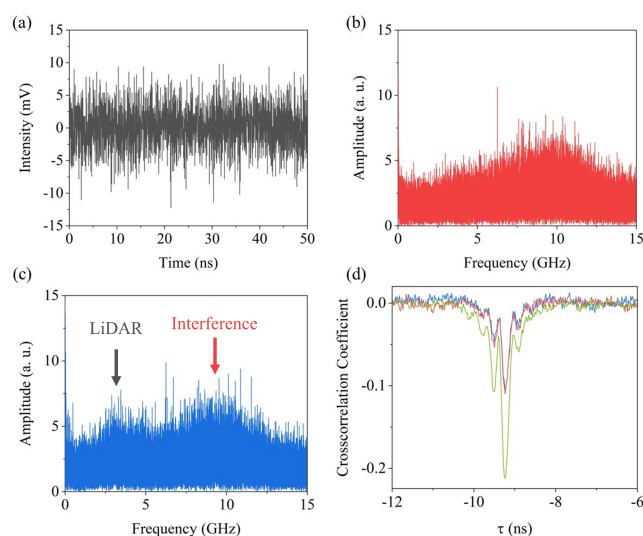


Figure 6. Evaluation of anti-interference capability in a multi-source environment: (a) the time trace of an intentional optical interference signal generated by an external 850 nm laser at $J = 73$ mA; (b) the corresponding RF spectrum of the interference; (c) the RF spectrum of the combined signal received by the detector; (d) the crosscorrelation function (CCF) under interference (black) and with varied interference intensity (blue).

This external interference was optically combined with the echo signal from the target and received by the detector. The RF spectrum of the combined signal (Figure 6c) reveals a clear spectral distinction: the chaotic LiDAR signal remains distinct near 2.7 GHz, whereas

the interference contributes broadband components that effectively act as additive noise across the detection band.

Notably, despite the presence of this strong interferer, the crosscorrelation function (CCF) between the TE and TM channels continues to exhibit a well-defined anti-correlation peak at the correct time delay corresponding to the target distance. Although a minor reduction in the CCF amplitude is observed—likely due to suboptimal alignment under mixed-signal conditions—the temporal position of the peak remains unchanged. This resilience is further demonstrated by varying the intensity of the interference source (blue curve in Figure 6d); even as the interference level changes, the anti-correlation peak retains its original time shift, confirming that the ranging information is preserved.

This robust behavior may originate from two key properties of our system: first, the pseudo-orthogonal and noise-like nature of the chaotic TM reference, which exhibits low crosscorrelation with the structured interference, and second, the common-mode rejection inherent in the dual-polarization correlation detection, which suppresses signals not shared by both the TE and TM paths. These results affirm that the proposed chaotic LiDAR architecture maintains accurate ranging functionality even in the presence of significant optical interference, underscoring its suitability for deployment in multi-user or ambient-light-rich environments.

4. Conclusions

In summary, we have successfully demonstrated a novel and highly adaptable chaotic LiDAR system based on the polarization-resolved dynamics of a semiconductor VCSEL with delayed orthogonal feedback. By exploiting the intrinsic TE- and TM-mode competition, our system generates a pair of complementary optical signals: a chaotic TM reference governed by amplified spontaneous emission and a modulated TE probe with deterministic delayed feedback wings.

The system exhibits remarkable versatility and flexibility, enabled by two key tuning mechanisms: the half-wave plate for precise polarization-coupling adjustment and the pump current for dynamic operation point selection. These controls allow real-time optimization of the crosscorrelation amplitude, signal-to-noise ratio, and detection sensitivity across a wide range of operational scenarios. Furthermore, the system maintains linear ranging performance with centimeter-level resolution and demonstrates strong resilience against external optical interference, confirming its suitability for deployment in spectrally congested or multi-user environments.

For practical application, monolithic integration with solid-state beam-steering hardware is necessary. Polarization-maintaining coated MEMS mirrors exhibit direct compatibility with our setup, on the condition that spurious back-reflections are attenuated by an optical isolator positioned upstream of the beam-steering module. We estimate a typical MEMS mirror insertion loss of 3–5 dB, which can be compensated by operating the VCSEL at higher current or integrating a semiconductor optical amplifier (SOA) pre-amplifier. Conventional optical phased arrays (OPAs) are plagued by severe polarization-dependent loss, yet a bespoke dual-polarization OPA architecture can separately route TE and TM modes to dedicated phase shifters. This constitutes a viable technical roadmap for future fully integrated realizations.

If we consider miniaturization, the external ring cavity can be substituted by a low-loss waveguide delay line on a photonic integrated circuit (PIC), shrinking the footprint from tens of centimeters to a few millimeters. All passive components, namely, beam splitters, polarizing beam splitters, mirrors, and wave plates, have waveguide-based counterparts that can be monolithically realized on a PIC chip; representative examples include directional couplers, polarization rotators and phase shifters. The VCSEL can be monolithically

integrated with the feedback waveguide. The entire system—including VCSEL, waveguides, phase shifters, and on-chip photodetectors—is amenable to co-fabrication on a single monolithic die, with a projected total power consumption of less than 5 W. This fully integrated platform would maximize the native simplicity and cost-efficient merits of the polarization feedback architecture we propose herein.

This innovative polarization-multiplexed approach eliminates the need for external modulators or complex coherent detection, significantly simplifying system architecture while enhancing robustness. Thus, our proposed LiDAR system is not only high-performing and accurate but also inherently low-cost, energy-efficient, and scalable—attributes that address key barriers to the widespread adoption of advanced ranging technologies. It holds significant promise for applications in autonomous navigation, robotic perception, and secure ranging.

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