

Simultaneous Generation of Low-Phase-Noise LO and Reconfigurable Radar Waveforms in a Polarization-Multiplexed Optoelectronic Oscillator

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Abstract—We propose and experimentally demonstrate a polarization-multiplexed optoelectronic oscillator (OEO) that simultaneously generates a Ku-band low-phase-noise local oscillator (LO) signal and X-band high-quality, reconfigurable wideband radar waveforms. The architecture employs a commercial dual-polarization binary phase shift-keying Mach-Zehnder modulator (DP-BPSK MZM), and two orthogonally polarized loops are formed with independently tuned center frequencies defined by electrical bandpass filters. The x-polarized loop generates a Ku-band 14-GHz single-tone LO exhibiting -144 -dBc/Hz single-sideband phase noise at a 10-kHz offset. In parallel, the y-polarized loop employs a wideband electrical bandpass filter to generate radar waveforms via either injection locking or active mode locking. Under injection locking, an X-band linear frequency-modulated (LFM) waveform centered at 8.5 GHz with a 2-GHz span (7.5–9.5 GHz) is obtained. Compared with the original LFM signal generated by the arbitrary waveform generator (AWG), the injected waveform benefits from the high- Q factor and filtering effect of the OEO loop, leading to a reduction of more than 40 dB in single-sideband phase noise and an improvement of about 20 dB in spectral signal-to-noise ratio (SNR). Active mode locking enables the generation of 9-GHz microwave pulse trains with repetition rates of 100 kHz, 500 kHz, and 1 MHz, exhibiting a phase noise of -144 dBc/Hz at a 10-kHz offset. Furthermore, staggered double- and triple-pulse sequences are realized by injecting position-encoded Gaussian-shaped waveforms from an AWG. These results confirm the potential of the proposed OEO for multifunctional applications in next-generation high-resolution and antijamming radar systems.

Index Terms—Active mode locking, injection locking, optoelectronic oscillator (OEO), phase noise, polarization multiplexing, radar waveform generation.

I. INTRODUCTION

RADAR systems are essential to modern technology, serving applications from military target detection and

tracking to infrastructure monitoring and autonomous driving [1], [2]. To meet growing demands for high-resolution imaging, precise velocity measurement, and multitarget discrimination, next-generation radar platforms require microwave sources that simultaneously deliver low-phase-noise local oscillator (LO) signals and reconfigurable wideband radar waveforms [3], [4]. The low-phase-noise LO provides a stable reference for frequency conversion, thereby enhancing sensitivity through improved signal-to-noise ratio (SNR), while also suppressing spectral broadening, spurious tones, and signal distortion [5], [6]. Moreover, employing a high-frequency LO supports wider instantaneous bandwidth and finer resolution, which is advantageous for advanced radar and high-capacity communication systems. Concurrently, high-quality reconfigurable wideband waveforms (e.g., linear frequency-modulated (LFM) signal and microwave pulse trains) enable fine range resolution, accurate imaging, extended velocity coverage, improved Doppler resolution, and stronger jamming immunity [7], [8], [9], [10]. Unifying these capabilities within a single architecture not only simplifies hardware design but also supports dynamic waveform reconfiguration and radar-communication integration [11]. Furthermore, by combining a single-tone signal for accurate velocity estimation with an LFM signal for high-resolution ranging and imaging, both range and velocity information can be simultaneously obtained, thereby avoiding range-velocity coupling in conventional schemes and enhancing system robustness in complex environments [12]. Therefore, there is a strong need for signal generation techniques that can simultaneously deliver low-phase-noise LO signals and reconfigurable radar waveforms within a compact and integrated architecture.

Traditional electronic techniques for generating such signals, such as phase-locked loops (PLLs) and direct digital synthesizers (DDSs), are fundamentally constrained by feedback delays and the limited bandwidth and resolution of digital-to-analog converters. These intrinsic bottlenecks restrict their frequency agility, bandwidth, and phase noise performance, thereby limiting their suitability for delivering the reconfigurable high-quality waveforms demanded by advanced multifunctional radar systems [13], [14], [15].

The optoelectronic oscillator (OEO), employing long, low-loss optical fiber delays as energy storage elements, offers an exceptionally high-quality factor and enables the generation of spectrally pure, ultralow-phase-noise microwave signals even

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at high frequencies [16], [17], [18]. Conventional OEOs are typically designed for single-tone generation, achieving low phase noise [16], [18], high side-mode suppression ratios (SMSRs) [19], [20], [21], and wide frequency tunability [22], [23], making them excellent LO candidates in radar and communication systems. In addition, modified OEO architectures have been developed to support multifunctional signal generation, including LFM waveforms and microwave pulses, which are particularly valuable in radar systems for achieving high range resolution and strong antijamming capability, as well as precise ranging and reliable target detection, respectively. For instance, Fourier-domain mode-locked OEOs [24], [25] generate LFM signals with large time–bandwidth products via tunable microwave photonic filters for precise chirp control, while active or passive mode locking can phase-locked multiple longitudinal modes to produce periodic, chirp-free microwave pulses with low timing jitter and high coherence [26], [27], [28], [29]. However, most existing OEO-based implementations focus on either the LO signal or the radar waveform generation in isolation. As modern radar systems evolve toward multifunctional and integrated platforms, there is a growing need for signal sources capable of simultaneously generating high-purity LO signals and reconfigurable radar waveforms.

We propose and experimentally demonstrate a polarization-multiplexed OEO capable of simultaneously generating a low-phase-noise LO signal and multiple high-quality, reconfigurable radar waveforms, including LFM signals and microwave pulse trains. The system employs a dual-polarization binary phase shift-keying (DP-BPSK) modulator to construct two orthogonally polarized oscillation loops that operate independently, enabling flexible waveform generation without cross-interference. Benefiting from the high-quality factor of the OEO architecture, the generated LO signal achieves a center frequency of 14 GHz with a phase noise of -144 dBc/Hz at a 10-kHz offset. Moreover, a 2-GHz-bandwidth LFM signal exhibits an enhancement of 20 dB in SNR and a reduction of 40 dB in phase noise compared with direct arbitrary waveform generator (AWG) injection. In addition, tunable-repetition-rate microwave pulse signals, as well as staggered double- and triple-pulse formats, are successfully generated. The generated pulse signal exhibits a phase noise performance better than -144 dBc/Hz at a 10-kHz offset. Thanks to the capability of simultaneously providing low-phase-noise LO signals and high-purity reconfigurable wideband radar waveforms, the proposed OEO architecture offers a promising solution for next-generation multifunctional radar systems, particularly in high-resolution and antijamming scenarios.

II. PRINCIPLE

The proposed system is illustrated in Fig. 1. A continuous-wave optical carrier from the laser diode (LD) is evenly split into two branches at the input of the DP-BPSK. Each branch is independently modulated by submodulators MZM-a and MZM-b. The output of MZM-b is rotated by 90° using a polarization rotator (PR), ensuring that the two signals are orthogonally polarized. These signals are then combined

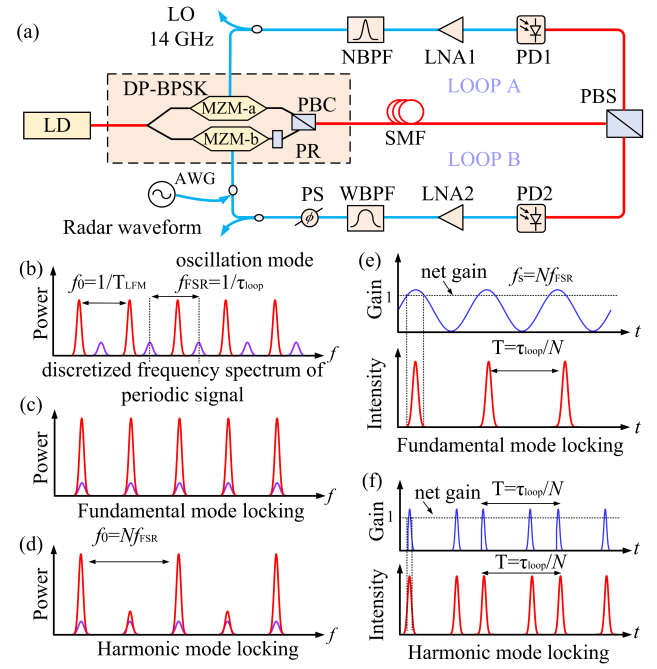


Fig. 1. (a) Schematic of the proposed polarization-multiplexed OEO for simultaneous generation of a low phase noise LO signal and high-quality wideband reconfigurable radar waveforms. (b) Frequency mismatch between the injected LFM comb lines (red) and the free-running OEO longitudinal modes (purple). (c) Fundamental injection locking condition with mode alignment. (d) Harmonic injection locking condition under high-order mode spacing. (e) Principle of single-loop microwave pulse generation. (f) Time-domain evolution of generated staggered microwave pulse waveforms with programmable positions. LD: laser diode; DP-BPSK: dual-polarization binary phase-shift-keying; MZM: Mach–Zehnder modulator; PR: polarization rotator; PBC/PBS: polarization beam combiner/splitter; SMF: single-mode fiber; PD: photodetector; LNA: low-noise amplifier; NBPF: narrow bandpass filter; and WBPF: wideband bandpass filter.

through a polarization beam combiner (PBC) to form a polarization-multiplexed optical carrier, which is transmitted through a long section of single-mode fiber (SMF) to provide the required delay. At the receiver side, a polarization beam splitter (PBS) separates the signal into two orthogonal paths, corresponding to loop-a and loop-b. In each loop, the optical signal is converted into an electrical signal by a photodetector (PD), followed by amplification and filtering via low-noise amplifiers (LNA1 and LNA2) and bandpass filters (NBPF and WBPF). In loop-a, the processed signal is directly reinjected into MZM-a, forming a closed feedback path that sustains single-frequency oscillation and enables the generation of a low-phase-noise LO signal. In loop-b, the filtered signal is combined with an external microwave signal from an AWG using an electrical coupler (EC), and the combined signal is fed back into MZM-b. This establishes another feedback loop, which supports the generation of wideband reconfigurable radar signals. Because the two loops operate on orthogonal polarizations, their resonance modes remain independent, ensuring that the signal generation in each loop proceeds without mutual interference.

The spectral representation of a periodic LFM signal is given by

$$S_{\text{LFM}}(f) = \sum_{n=-\infty}^{+\infty} C_n \delta(f - f_n), \quad f_n = f_c + n f_0 \quad (1)$$

where f_c denotes the carrier frequency, $f_0 = 1/T_{\text{LFM}}$ is the frequency spacing determined by the LFM repetition period T_{LFM} , as illustrated in Fig. 1(b), and C_n represents the complex Fourier coefficient associated with the n th spectral line. From the spectral structure of a periodic LFM signal, it can be observed that its spectrum consists of a series of discrete frequency components equally spaced by the inverse of the LFM repetition period. Similarly, as a ring-type oscillator, the OEO supports a set of longitudinal cavity modes that are also uniformly distributed in frequency. The spacing between adjacent longitudinal modes is determined by the inverse of the loop round-trip delay, expressed as $f_{\text{FSR}} = 1/\tau_{\text{loop}}$, where τ_{loop} represents the OEO loop delay. Accordingly, the resonant longitudinal modes in the OEO loop can be written as [16]

$$f_{\text{OEO}} = mf_{\text{FSR}} \quad (2)$$

where m is an integer. To enable effective injection locking of the OEO longitudinal modes by the injected LFM signal, the cavity modes must be properly aligned with the spectral lines of the LFM frequency comb. Under this condition, each discrete spectral component of the LFM waveform can pull and lock the corresponding free-running OEO mode, forcing it to synchronize to the injected frequency. As a result, the OEO output spectrum is reshaped by the LFM frequency comb through frequency pulling and injection locking. This alignment requires the spacing of the LFM frequency comb to match an integer multiple of the OEO FSR, $f_0 = Nf_{\text{FSR}}$, where N is an integer. When the frequency offset between an injected LFM comb line and a free-running OEO longitudinal mode falls within the injection-locking bandwidth, that cavity mode can be stably locked to the injected signal. The maximum locking range of the injection-locked OEO is expressed as [30]

$$\Delta f_{0,\text{max}} = \frac{\Delta f_{\text{FSR}}}{2} \cdot \frac{E_{\text{inj}}}{E_{\text{osc}}} \quad (3)$$

where $\Delta f_{0,\text{max}}$ denotes the maximum locking range of the injection-locked OEO, and E_{osc} and E_{inj} are the amplitudes of the selected longitudinal mode in the free-running OEO and the injected microwave signal, respectively. As shown in Fig. 1(b), when the injected LFM signal fails to satisfy the injection-locking condition, its discrete frequency components become misaligned with the longitudinal modes of the OEO. As a result, the unmatched modes remain unlocked and are not amplified by the OEO [31]. By precisely adjusting the phase shifter, the longitudinal modes of the OEO can be effectively locked to the injected signal, as illustrated in Fig. 1(c). On the one hand, the OEO loop features a high-quality factor, enabling strong frequency-selective resonant enhancement for external components matching the intrinsic modes. Even weak signals can be coherently accumulated and significantly amplified over multiple round trips [32], [33]. On the other hand, once injection locking is established, the oscillation frequency synchronizes with the injected signal, and the loop feedback further amplifies matched components while suppressing nonresonant modes—a phenomenon also observed in harmonic mode locking. Therefore, for an LFM signal comprising multiple frequency components, each comb line can be individually phase-locked and coherently strengthened by the corresponding OEO mode, enabling uniform gain

and substantial SNR improvement across the entire bandwidth. Based on the injection-locking theory, the phase noise of the resulting LFM signal can be expressed as [30]

$$S_{\text{osc}}(f) = \frac{1}{1 + (f/\Delta f_{0,\text{max}})^2} S_{\text{inj}}(f) + \frac{1}{1 + (\Delta f_{0,\text{max}}/f)^2} S_{\text{free}}(f) \quad (4)$$

where f is the frequency offset, and $S_{\text{inj}}(f)$ and $S_{\text{free}}(f)$ are the phase noise power spectra of the injected microwave signal and the free-running OEO, respectively. According to (4), the near-carrier phase noise of the injection-locked OEO is primarily influenced by the phase noise of the injected signal, while the far-from-carrier phase noise is dominated by the intrinsic noise of the free-running OEO. The characteristics of the LFM signal generated by the OEO are fully determined by the parameters of the injected waveform. Harmonic mode locking, as illustrated in Fig. 1(d), occurs when the cavity round-trip delay of the OEO is matched to an integer multiple of the period of the injected signal, ultimately enabling the generation of LFM signals with tunable periods. Furthermore, the chirp slope of the output LFM waveform can be flexibly tuned by adjusting the chirp rate of the injected LFM signal.

By modifying the waveform applied from the AWG, the OEO-generated radar signal can be dynamically reconfigured. Assuming that a sinusoidal signal with frequency ω_s is injected into the OEO loop, the output optical signal from the MZM-b can be expressed as

$$E_{\text{out}}(t) = E_0 \exp(j\omega_c t) \cos \left[\frac{\pi}{2V_\pi} V_{\text{in}}(t) + \frac{\pi V_{\text{AWG}}}{2V_\pi} \cos(\omega_s t + \varphi) + \frac{\pi V_{\text{DC}}}{2V_\pi} \right] \quad (5)$$

where E_0 and ω_c are the amplitude and angular frequency of the optical carrier, respectively. V_π is the half-wave voltage of the DP-BPSK modulator, $V_{\text{in}}(t)$ is the generated signal within the loop, V_{DC} is the dc offset voltage, and V_{AWG} and φ are the amplitude voltage and initial phase of the microwave signal generated by AWG, respectively. According to the principle of active mode locking [29], the frequency of the injected sinusoidal signal should satisfy $f_s = Nf_{\text{FSR}}$ ($N = 1, 2, 3, \dots$), and the signal obtained after a cycle in the OEO loop can be written as

$$V_{\text{out}}(t) = V_{\text{ph}} \left\{ 1 + \cos \left[\frac{\pi}{2V_\pi} V_{\text{in}}(t) + \frac{\pi V_{\text{DC}}}{2V_\pi} + \frac{\pi V_{\text{AWG}}}{2V_\pi} \cos(\omega_s t + \varphi) \right] \right\} \quad (6)$$

where $V_{\text{ph}} = 0.5G_A R \Re P_c \exp(-\alpha L)$, G_A is the voltage gain of the electric amplifier, and $\Re$ and R are the responsivity and impedance of the PD, respectively. α and L are the loss coefficient and the length of the optical fiber, respectively. Thus, the open-loop small-signal gain of the OEO in the time domain can be calculated as

$$G_s = \frac{dV_{\text{out}}}{dV_{\text{in}}} \bigg|_{V_{\text{in}}=0} = -\frac{\pi V_{\text{ph}}}{V_\pi} \sin \left[\frac{\pi V_{\text{DC}}}{V_\pi} + \frac{\pi V_{\text{AWG}}}{V_\pi} \cos(\omega_s t + \varphi) \right]. \quad (7)$$

It can be seen from (7) that the open-loop gain G_s is dynamically modulated by the injected signal. Fig. 1(e) shows the gain curve when the period of the injected signal is equal to the loop delay of OEO. When the modulation frequency is an integer multiple of the OEO's FSR, the microwave signals within the net-gain region (gain >1) are selectively amplified during each loop iteration, ultimately leading to the formation of a periodic pulse train synchronized with the injected modulation signal. Notably, by tailoring the waveform of the injected signal, the temporal positions where the OEO loop gain exceeds unity can be selectively modulated. As a result, the temporal positions of the generated pulses can be flexibly controlled, enabling the synthesis of arbitrarily positioned or staggered microwave pulses, as illustrated in Fig. 1(f).

III. EXPERIMENT

An experimental setup, illustrated in Fig. 1(a), was constructed to validate the proposed architecture. A continuous-wave laser source (NXDFB-1550-100-MOD) operating at 1550 nm with an output power of 21 dBm was employed. The optical carrier was fed into a DP-BPSK (Fujitsu FTM7980EDA), where it was equally split into two branches and individually modulated by the two internal sub-MZMs (MZM-a and MZM-b), both biased at their quadrature points. Following modulation in MZM-b, the polarization state of the signal was rotated by 90° using a PR. The orthogonally polarized signals were then combined by a PBC, forming a polarization-multiplexed optical signal. This signal was transmitted through a 2-km SMF, providing the required delay for the OEO. At the output, the delayed signal was converted into electrical signals by two PDs (DSC40S), one in each loop. These signals were amplified by low-noise electrical amplifiers (Marki APM-7098PA) to ensure sufficient loop gain. In loop A, an electronic bandpass filter with a center frequency of 14 GHz and a 3-dB bandwidth of 11 MHz was used to extract the LO signal. In loop B, a WBPf centered at 8.5 GHz with a 3-dB bandwidth of 2 GHz was employed to select the radar signal. The filtered signal was combined with an AWG-generated waveform (Tektronix AWG70001A) via a coupler and reinjected into MZM-b. Two 50:50 couplers enabled real-time monitoring, while the signal spectra were measured using an R&S FSWP26 analyzer.

An LFM signal generated by an AWG is configured with a period of 10 μ s, precisely matched to the round-trip delay of the OEO loop. The center frequency and bandwidth are set to 8.5 and 2 GHz, respectively, and the amplitude of the injected LFM signal is 210 mV. Meanwhile, the phase shifter inside the loop is adjusted to ensure that the frequency components of the injected LFM signal fall accurately within the injection locking range of the OEO's longitudinal modes. To achieve maximum loop gain and efficient modulation, both sub-MZMs within the DP-BPSK are biased at their quadrature points. As illustrated in Fig. 2(a), the system enables the simultaneous generation of an 8.5-GHz-centered LFM waveform with a 2-GHz bandwidth and a 14-GHz LO signal. The temporal waveform of the LFM signal, captured

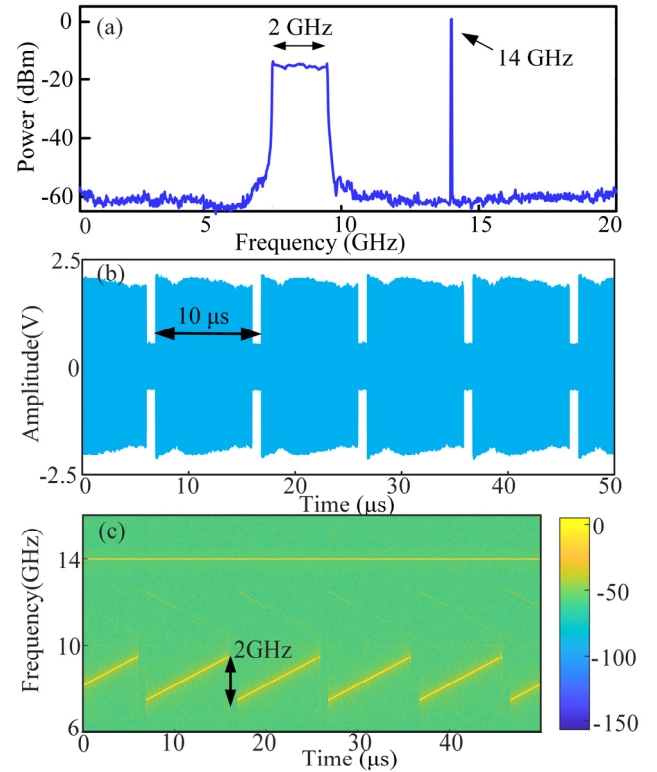


Fig. 2. Experimental results of the generated LFM and LO signals. (a) Spectrum showing an 8.5-GHz LFM signal with a 2-GHz bandwidth and a 14-GHz LO signal. (b) Time-domain waveform of the LFM signal with a 10- μ s period. (c) Time-frequency spectrogram showing the LFM up-chirp and the 14-GHz LO signal.

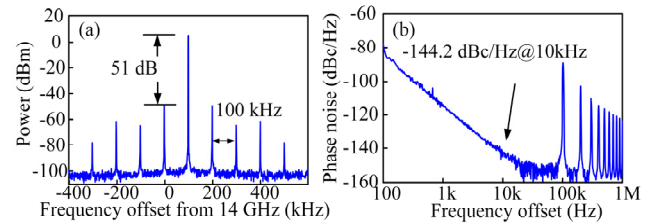


Fig. 3. Performance of the generated 14-GHz LO signal. (a) Electrical spectrum with a span of 1 MHz and a resolution bandwidth (RBW) of 100 Hz. (b) Phase noise spectrum of the LO signal.

using an oscilloscope and shown in Fig. 2(b), exhibits a period of approximately 10 μ s, verifying its synchronization with the OEO loop delay. The time-frequency spectrogram in Fig. 2(c), obtained via short-time Fourier transform, clearly demonstrates a linear up-chirp profile of the generated LFM signal. Simultaneously, the presence of the 14-GHz LO signal is evident in the time-frequency domain, further verifying the proposed scheme's capability to generate high-frequency LO signals and wideband LFM radar waveforms concurrently.

Fig. 3(a) shows the spectrum of the 14-GHz LO signal generated in loop A, exhibiting an SMSR of 51 dB and a mode spacing of 100 kHz, consistent with the 2-km fiber delay. The measured phase noise at a 10-kHz offset is -144 dBc/Hz, as shown in Fig. 3(b). The low-phase-noise 14-GHz

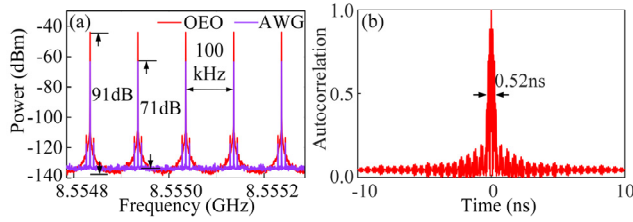


Fig. 4. (a) Electrical spectra of the LFM waveforms generated by the proposed injection-locked OEO (red curve) and the AWG (purple curve) with a span of 500 kHz and an RBW of 5 Hz. (b) Autocorrelation result of the generated LFM waveform, showing a 3-dB compressed pulsewidth.

Ku-band signal offers distinct advantages for radar systems, including enhanced detection sensitivity, improved range and velocity accuracy, coherent integration of weak targets, and reduced distortion in high-resolution imaging and Doppler processing. Owing to its wide instantaneous bandwidth and high spatial resolution, this signal is particularly attractive for next-generation radar and integrated radar–communication platforms.

Fig. 4(a) shows the spectra of the LFM signals generated by the proposed OEO (red curve) and the AWG (purple curve). The spacing between adjacent longitudinal modes is 100 kHz, determined by the cavity delay. When the comb lines of the injected LFM signal fall within the injection-locking range of the OEO, they are phase-locked to the oscillator, enabling coherent enhancement with noise performance referenced to the intrinsic noise floor of the OEO [31], [32]. Consequently, the SNR of the output signal is markedly improved. This improvement arises from the OEO's high- Q resonance and loop filtering, which selectively amplify the locked modes aligned with the injected waveform while suppressing out-of-band noise and unlocked modes. In addition, the intrinsic loop gain further boosts the coherently aligned spectral components, enhancing the signal strength without raising the noise floor. This mechanism enables the generation of LFM signals with exceptionally high SNR, which is particularly beneficial for radar systems requiring enhanced detection sensitivity and strong antijamming performance. The SNR of the LFM signal generated by the OEO reaches 91 dB, which is 20 dB higher than that of the LFM signal generated solely by the AWG. A high SNR LFM signal significantly enhances the radar system's resistance to interference and extends its detection range [10]. As illustrated in Fig. 4(b), the autocorrelation of the up-chirp LFM signal yields a 3-dB compressed pulsewidth of approximately 0.52 ns.

To accurately characterize the phase-noise performance of the LFM signals generated by the AWG and the OEO, the pulse signal phase-noise measurement mode of the FSWP analyzer was employed since the wide bandwidth and time-varying instantaneous frequency of the generated LFM waveforms render the single-tone measurement mode unsuitable. In this mode, the measurable frequency-offset range is limited to approximately 0.7 times the repetition rate of the LFM signal. Fig. 5 presents a comparison of the measured phase-noise spectra of the LFM signals generated by the AWG (purple curve) and the injection-locked OEO (red curve). At

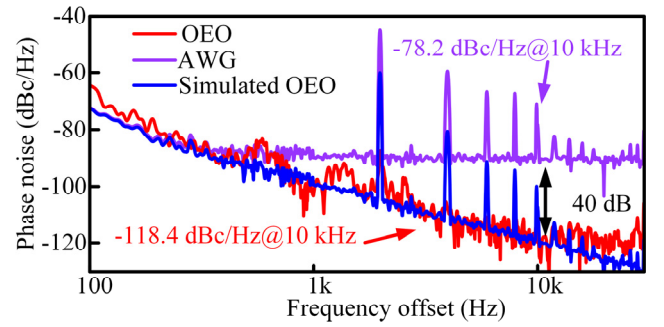


Fig. 5. Phase noise spectra of the LFM signals generated by the AWG (purple curve), the injection-locked OEO (red curve), and the theoretically simulated injection-locked OEO output (blue curve), measured using the pulse phase-noise mode of the FSWP.

a 10-kHz frequency offset, the injection-locked OEO exhibits a phase noise of approximately -118.2 dBc/Hz, representing an improvement of about 40 dB compared with the AWG-generated LFM signal. At low-frequency offsets, the phase noise of the injection-locked OEO closely follows that of the injected signal, which is consistent with the theoretical prediction of (4) and confirms that the near-carrier phase noise is dominated by the injected source. Furthermore, the analytical phase-noise expression in (4) is used to calculate the theoretical phase-noise spectrum of the injection-locked LFM signal, which is plotted as the blue curve in Fig. 5. The calculated spectrum shows good agreement with the experimental results over the entire frequency-offset range, indicating that the proposed analytical model provides a reliable approximation of the noise-transfer behavior in the injection-locking process. It is also observed that the measured spectrum does not exhibit the pronounced peaks predicted by the simulation at large frequency offsets. This discrepancy can be attributed to the intrinsic loop-filtering effect of the OEO, which suppresses spurious frequency components that are not aligned with the longitudinal cavity modes, resulting in a smoother far-offset noise floor in the experimental measurement.

Tunable-period LFM signals enhance radar systems by improving antijamming capabilities and environmental adaptability. However, with a fixed optical fiber length of 2 km in the OEO, the FSR of the loop is limited to 100 kHz. Adjusting the period of the output LFM signal would require modifying the fiber length, which increases system complexity and reduces reconfigurability. To address this, a harmonic mode-locking technique can be employed in the injection-locked OEO to achieve tunable LFM periods. By setting $f_0 = Nf_{FSR}$ (N is an integer and $N \geq 2$), longitudinal modes with a frequency interval of f_0 are injected-locking by the AWG-generated LFM signal, effectively increasing the mode spacing to Nf_{FSR} . Fig. 6(a) and (b) shows the spectra of the LFM signal under second-order harmonic mode locking and fifth-order harmonic mode locking, corresponding to mode spacings of 200 and 500 kHz, respectively. Notably, as shown in Fig. 6(a) and (b), several weak and unexcited modes are observed between the dominant oscillating longitudinal modes, corresponding to the free-running longitudinal modes

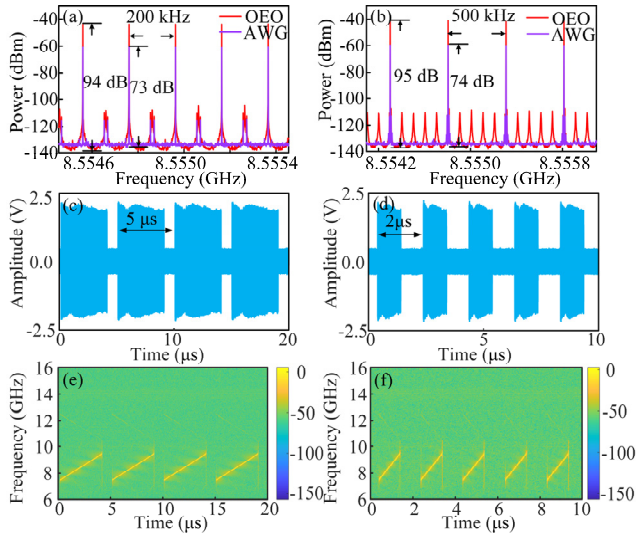


Fig. 6. Measured spectra, temporal waveform, and spectrogram of the generated LFM under second-order harmonic mode locking (a), (c), and (e) and fifth-order harmonic mode locking (b), (d), and (f).

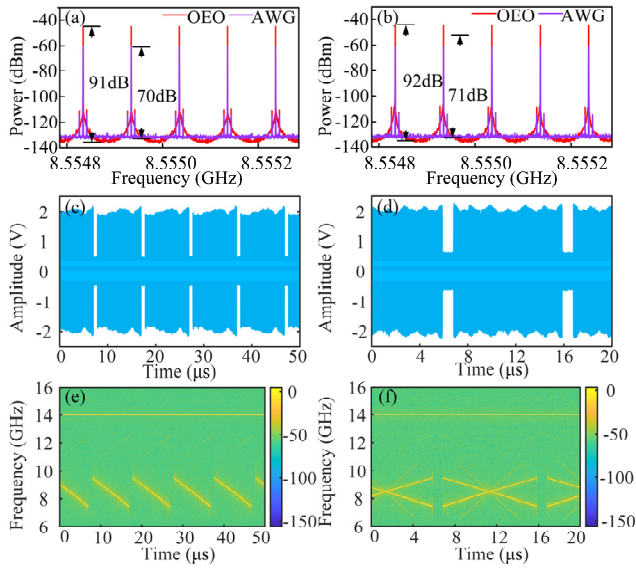


Fig. 7. Measured results of the generated down-chirp and dual-chirp LFM signals. Spectrum of the down-chirp (a) and dual-chirp (b) LFM signals. Temporal waveform of the down-chirp (c) and dual-chirp (d) LFM signals. Spectrogram of the down-chirp (e) and dual-chirp (f) LFM signals.

of the OEO, which are not injection-locked by the AWG signal. Such spurious modes can be effectively suppressed by employing a dual-loop OEO architecture [19], where two loops with slightly different round-trip delays create a Vernier-effect filtering response. The periods of the LFM signals generated by the IL-OEO under harmonic mode locking, as illustrated in Fig. 6(b) and (d), are 5 and 2 μ s, respectively. These periods correspond to one-half and one-fifth of the OEO cavity round-trip time, in agreement with harmonic mode-locking theory. The corresponding spectrograms of the generated LFM signals are presented in Fig. 6(e) and (f). Moreover, a 14-GHz LO signal is simultaneously generated.

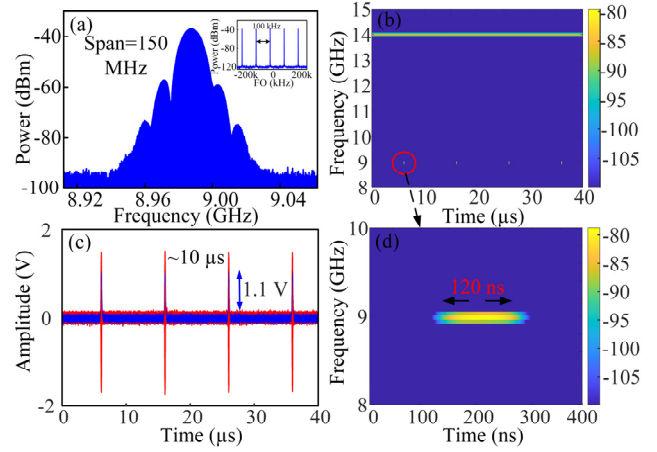


Fig. 8. Measured results of the generated microwave pulse signal. (a) Electrical spectrum. (b) Frequency-time diagram showing the coexistence of the 14-GHz LO signal and the microwave pulse signal. (c) Temporal waveform. (d) Zoomed-in view of the frequency-time diagram.

Switchable multifunction chirp LFM signals enhance radar system adaptability while greatly improving antijamming capabilities [34], [35]. By adjusting the chirp parameters of the LFM signals generated by the AWG, corresponding high-quality LFM waveforms can be produced through the IL-OEO. As shown in Fig. 7(a), the spectrum of a down-chirp LFM signal indicates that the SNR of the IL-OEO-generated LFM signal is 21 dB higher than that of the LFM signal generated by the AWG. The temporal waveform of the down-chirp LFM signal is depicted in Fig. 7(c). The spectrogram in Fig. 7(e) demonstrates that the down-chirp LFM signal, with a bandwidth of 2 GHz, coexists effectively with a single-frequency signal at 14 GHz. Compared to single-chirp LFM signals, utilizing dual-chirp microwave waveforms in radar systems can significantly enhance range-Doppler resolution. A high-quality dual-chirp LFM signal can also be generated by injecting a dual-chirp LFM signal into the OEO loop via the AWG. Fig. 7(b) shows the temporal waveform of the dual-chirp LFM signal. The spectrogram of the generated signal, as illustrated in Fig. 7(f), confirms the coexistence of up- and down-chirp LFM signals, each with a bandwidth of 2 GHz. The generated dual-chirp LFM signal also achieves a 21-dB SNR enhancement compared with the LFM signal directly produced by the AWG.

To verify the reconfigurability of the proposed system, active mode locking was employed to generate microwave pulse signals. A waveform with a Gaussian envelope and a period of 10 μ s, shown as the blue curve in Fig. 8(c), was injected into the OEO loop using an AWG. According to (3), the oscillating microwave signal is selectively amplified at the peaks of the injected waveform, where the loop gain exceeds unity [29], leading to the formation of a periodic pulse train, shown as the red curve in Fig. 8(c). The measured electrical spectrum in Fig. 8(a) exhibits a smooth and stable envelope, indicating a favorable mode-locking state. The zoomed-in view of Fig. 8(a) shows a mode spacing of 100 kHz, corresponding to the FSR of the OEO loop, confirming fundamental

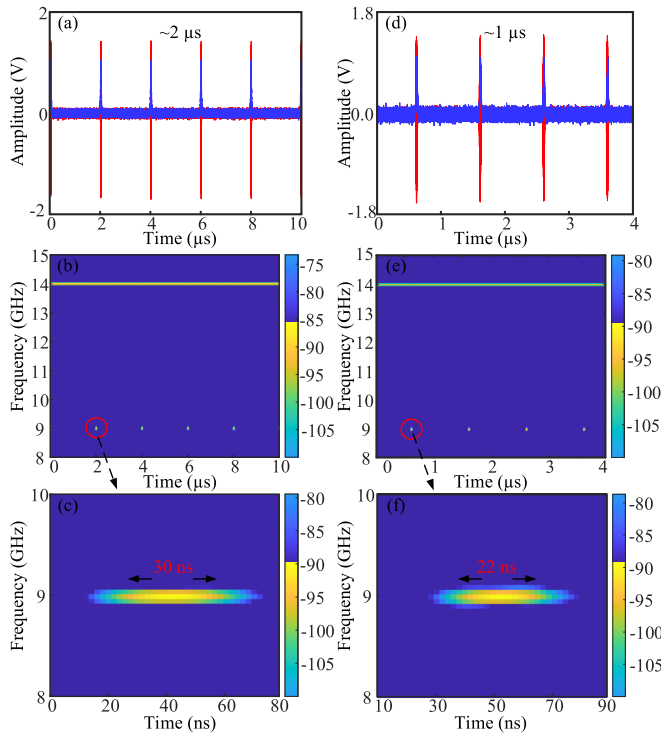


Fig. 9. Measured microwave pulse signals under harmonic mode locking. (a) Temporal waveform under fifth-order mode locking. (b) Frequency-time diagram under fifth-order mode locking. (c) Zoomed-in frequency-time view of (b). (d) Temporal waveform under tenth-order mode locking. (e) Frequency-time diagram under tenth-order mode locking. (f) Zoomed-in frequency-time view of (e).

mode-locking operation. The temporal waveform in Fig. 8(c) shows a pulse period of $\sim 10 \mu\text{s}$, consistent with the injected waveform and loop delay. To further examine simultaneous signal generation, the 14-GHz continuous-wave LO from loop A and the 9-GHz pulse train from loop B were combined using an electrical combiner. The composite signal was analyzed via short-time Fourier transform, as shown in Fig. 8(d). The frequency-time diagram clearly demonstrates the coexistence of a 14-GHz single-frequency signal and a periodic 9-GHz pulse train. The diagram clearly demonstrates the coexistence of a 14-GHz single-frequency signal and a periodic 9-GHz pulse train. The zoomed-in view of Fig. 8(d) reveals individual pulses with a duration of $\sim 120 \text{ ns}$. Such narrow pulse widths offer significant advantages for high-resolution radar ranging and multitarget discrimination, providing enhanced temporal resolution and improved antijamming performance.

In pulse-Doppler radar systems, microwave pulse signals with tunable pulse repetition frequency (PRF) are essential for improving multitarget resolution and extending velocity measurement range, as they allow flexible control over the pulse interval [36]. In our system, the PRF can be adjusted by varying the frequency of the electrical signal generated by the AWG. Specifically, external modulation signals with frequencies of 500 kHz and 1 MHz, as shown by the blue curves in Fig. 9(a) and (d), enable fifth- and tenth-order harmonic mode locking ($N = 5$ and $N = 10$), respectively. The resulting microwave pulse signals under these two locking states are shown as the red curves in Fig. 9(a) and (d). The

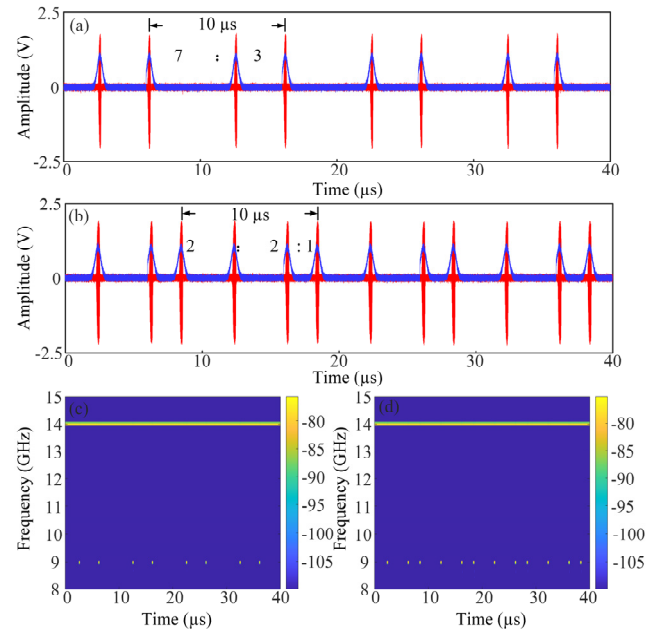


Fig. 10. Measured staggered microwave pulse signals. (a) Temporal waveform of the staggered double-pulse sequence. (b) Temporal waveform of the staggered triple-pulse sequence. (c) Frequency-time diagram of the double-pulse signal and 14-GHz LO signal. (d) Frequency-time diagram of the triple-pulse signal and 14-GHz LO signal.

pulse repetition periods are measured to be approximately 2 and $1 \mu\text{s}$, corresponding precisely to the inverse of the injection signal frequencies. The frequency-time diagrams in Fig. 9(b) and (e) further confirm the simultaneous generation of a 14-GHz single-frequency LO signal and a microwave pulse signal centered at 9 GHz. Fig. 9(c) and (f) presents zoomed-in frequency-time diagrams of the generated pulse signals under fifth- and tenth-order harmonic mode locking, respectively. The pulse widths are further compressed to approximately 30 and 22 ns, highlighting the capability of the proposed system to flexibly tailor pulse parameters without modifying the OEO loop length. This feature is particularly advantageous for high-resolution and adaptive radar applications.

Microwave pulse signals with a fixed PRF are fundamentally constrained by the tradeoff between maximum unambiguous range and velocity. A high PRF leads to range ambiguity, while a low PRF causes velocity ambiguity, posing a significant performance bottleneck in high-resolution radar systems [37]. To address this issue, staggered pulse waveforms have been introduced, which incorporate multiple pulses with nonuniform temporal intervals within each repetition cycle. This approach significantly extends the maximum unambiguous velocity while incurring only a slight compromise in the maximum unambiguous range [37], [38]. In this work, programmable staggered microwave pulse sequences are generated by tailoring the Gaussian waveform injected into the OEO loop. When the injected Gaussian waveform is designed to contain two peaks with unequal temporal separations within one period [as shown by the blue trace in Fig. 10(a)], the system produces a staggered double-pulse sequence with a nonuniform intragroup structure [as indicated by the red trace in Fig. 10(a)]. Likewise,

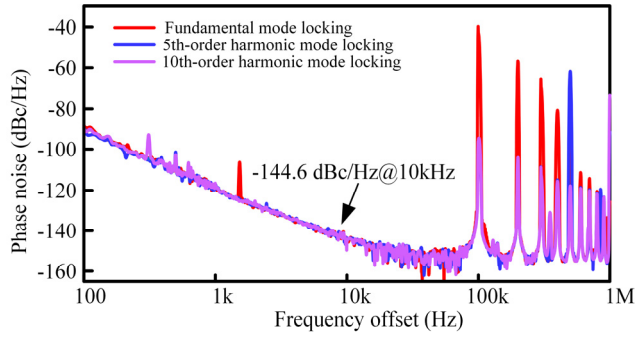


Fig. 11. Measured single-sideband phase noise of the generated microwave signals at 9 GHz from an actively mode-locked OEO.

configuring the injected Gaussian waveform to include three peaks with distinct temporal intervals enables the generation of a staggered triple-pulse sequence, as illustrated in Fig. 10(b). The frequency–time diagram clearly demonstrates the coexistence of a 14-GHz single-frequency signal and a periodic 9-GHz pulse train. The diagrams in Fig. 10(c) and (d) clearly confirm the simultaneous generation of programmable staggered microwave pulses and a 14-GHz continuous-wave LO signal.

Fig. 11 presents the single-sideband phase noise spectra of the microwave pulse signals under various harmonic mode-locking orders. The phase noise characteristics remain consistent across different mode-locking states, exhibiting levels better than -144 dBc/Hz at a 10-kHz offset frequency. The generation of low-phase-noise microwave pulse signals is critical for enhancing the resolution and reliability of radar systems, particularly in long-range detection and multitarget discrimination scenarios. Reduced spurious noise contributes to improved accuracy in both range and velocity estimation, enhanced antijamming performance, and increased robustness in target detection and tracking applications [39], [40].

IV. CONCLUSION

In this work, we propose and experimentally demonstrate a polarization-multiplexed OEO capable of simultaneously generating low-phase-noise single-frequency LO signals and reconfigurable radar waveforms. The use of a single modulator results in a compact architecture, while polarization multiplexing enables independent oscillation in two orthogonal loops without mutual interference. Thanks to the high- Q fiber loop, the generated 14-GHz LO signal achieves a phase noise of -144 dBc/Hz at a 10-kHz offset. By injecting an LFM waveform whose period matches the loop delay, the OEO achieves injection locking, producing LFM signals with matching center frequency, chirp rate, and bandwidth. The output LFM waveform exhibits an improvement of 20 dB in SNR and a reduction of 40 dB in phase noise compared with the injected signal. Furthermore, active mode locking enables the generation of microwave pulse trains with repetition rates of 100 kHz, 500 kHz, and 1 MHz, while staggered double- and triple-pulse sequences are realized by injecting position-encoded Gaussian-shaped waveforms from an AWG. These results confirm the proposed OEO's potential

for multifunctional radar in next-generation high-resolution and antijamming radar systems.

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