Frequency-Comb-Enabled Photonic RF Memory for Multi-False-Target Radar Compound Jamming

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Abstract: We report the first all-optical multi-false-target radar jamming scheme using frequency-comb-enabled photonic RF memory. More than 10 false targets with range-velocity deception information are obtained, with storage time exceeding 840μs and signal frequency reaching 16GHz.

1. Introduction

As the most widely used solution for electronic countermeasures, the current digital RF memory (DRFM) is mainly limited by the sampling rate of DACs/ADCs [1]. The instantaneous bandwidth (IBW) of DRFM can only reach 1-2 GHz typically, making it difficult to effectively jam spread spectrum radar signals such as frequency diversity and frequency agility. Microwave photonics offers an attractive approach to overcome the above rate and bandwidth limitations. A photonic RF memory (PRFM) can be implemented based on binary fiber optic delay lines [2,3] or active fiber optic loops [4-6], and its IBW can be extended beyond 10 GHz. However, only range deception can be achieved just through fiber delay, and cannot effectively cope with radars with simultaneous detection capabilities of range and velocity information, such as pulse Doppler radar. To address this problem, a Doppler frequency shift (DFS) structure based on dual-AOM has been proposed and combined with PRFM [5,6]. These schemes experimentally demonstrated high-fidelity frequency memory and tunable DFS, possessing the ability to perform range and velocity deception synchronously. Nevertheless, the DFS produced by AOMs is fixed each time, and only one Doppler false target can be generated, severely limiting the jamming effects. Additionally, increasing the storage period of signals with higher frequencies remains a critical issue.

In this paper, we put forward a frequency-comb-enabled PRFM system, achieving multiple false targets with deceptive range and velocity information in the all-optical domain for the first time, and it can be used to realize range-velocity compound deception radar jamming. The experimental results show that our method has remarkable storage and jamming performance. When a 300 m optical fiber was used as the loop, by separating the carrier and optimizing the filter bandwidth configuration, the maximum storage time can exceed 840 μs with an SNR degradation of less than 10 dB, the signal frequency can reach 16 GHz or even higher. Meanwhile, the Doppler frequency can be tuned from 5-12.5 MHz, and more than 10 false targets with different range-velocity deception information can be obtained simultaneously, significantly enhancing the ability for radar jamming.

2. Operation Principle

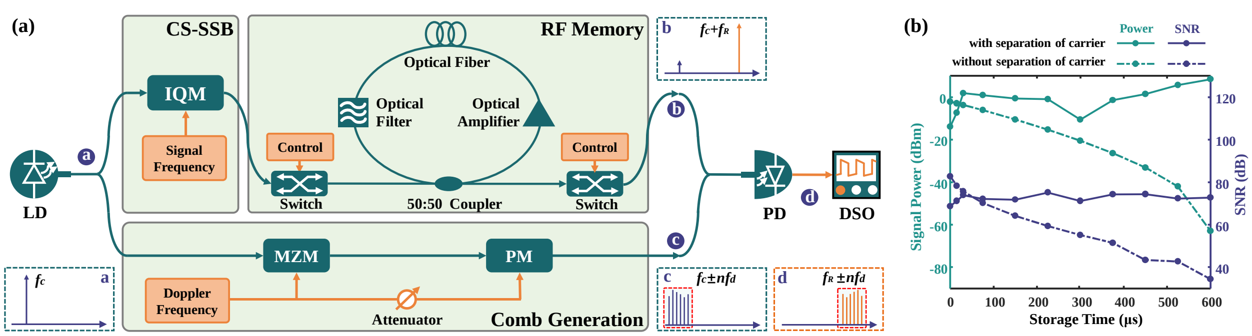

Fig. 1. (a) Experimental setup of the frequency-comb-enabled PRFM system for multi-false-target radar compound jamming. (b) Simulated power and SNR changes of a stored 20 GHz signal in different schemes.

The main idea of our method is independent processing of the signal and the carrier, which can reduce noise accumulation by storing the signal separately and can generate multiple deceptive false targets by comb modulation of the carrier. Fig. 1(a) illustrates the experimental setup of the frequency-comb-enabled PRFM system for range-velocity compound deception radar jamming. An optical carrier f_c generated by an LD is split into two paths, one of the carriers is sent to an in-phase/quadrature modulator (IQM) biased at the quadrature transmission point. The received RF signal f_R is modulated on the optical carrier by the IQM, while the RF signals injected into the upper and lower arms of the IQM should have the same amplitude and quadrature phase difference to produce carrier-suppressed single-sideband (CS-SSB) modulation, and the separation of carrier and signal is then achieved. The CS-SSB signal can be expressed as: $E_{signal} = E_s \exp[j2\pi(f_c + f_R)t]$, where E_s is the signal amplitude. The CS-SSB signal is launched into an active fiber optic loop for storage, which consists of a 50:50 optical coupler, a standard single-mode fiber (SSMF), an optical amplifier, and an optical filter. The entire loop is sequentially controlled by external clock signals via input/output optical switches with a high extinction ratio, and the modulated signal is switched in/out of the loop at a specified time to obtain range false target or range gate pull-off deception information.

Noting that thanks to the separation of carrier and signal, the theoretical bandwidth of the filter in our solution can be significantly narrowed compared to storing both the carrier and the high-frequency signal in the loop, resulting in most of the out-of-band noise being filtered out, with enormous potential for expanding the storage capacity. This idea is compatible with signals of any frequency, and an illustrative simulation result of a stored 20 GHz signal is shown in Fig. 1(b). It is worth mentioning that due to the equipment limitations, an AOM was used as the optical switch inside the loop in our experiments, and an undesired frequency shift will be applied to the signal each time when passes through the AOM. Therefore, the frequency-stepped signal will eventually fall outside the oscilloscope bandwidth and produce a sharp reduction in the monitored power, as a major limitation on storage capacity. Afterward, the AOM-based optical switch can be replaced by high extinction ratio gated SOA without any frequency modulation, hence the frequency of the signal is just limited by the modulator bandwidth theoretically.

The other carrier is sent to cascade modulators to configure the Doppler frequency comb. A Doppler frequency signal f_D is modulated on the optical carrier by a cascade of Mach-Zehnder modulator (MZM) and phase modulator (PM) to generate multiple optical comb lines [7], and the generated Doppler frequency comb carrier can be expressed as: $E_{carrier} = \sum_{n=0}^{\infty} E_n \exp[j2\pi(f_c \pm nf_d)t]$, where E_n is the amplitude of each comb. The Doppler frequency comb carrier and the RF-modulated signal are then detected by a wideband photodetector (PD), the beat signal can be described as: $I_{beat} = \sum_{n=0}^{\infty} I_n \exp[j2\pi(f_R \pm nf_d)t]$, where I_n is the amplitude of each false target. As compared with the received initial RF signal, the recovered RF signal produces multiple coherent copies containing different Doppler false target deception information. Therefore, range-velocity compound deception radar jamming with multiple false targets can be realized by combining the previously described storage procedures. Besides, compared to the AOM-based DFS [5], our solution for Doppler frequency comb generation has more precise frequency modulation and more flexible tunability, with the effectiveness of electronic countermeasures in more complex environments.

3. Experimental Results and Discussion

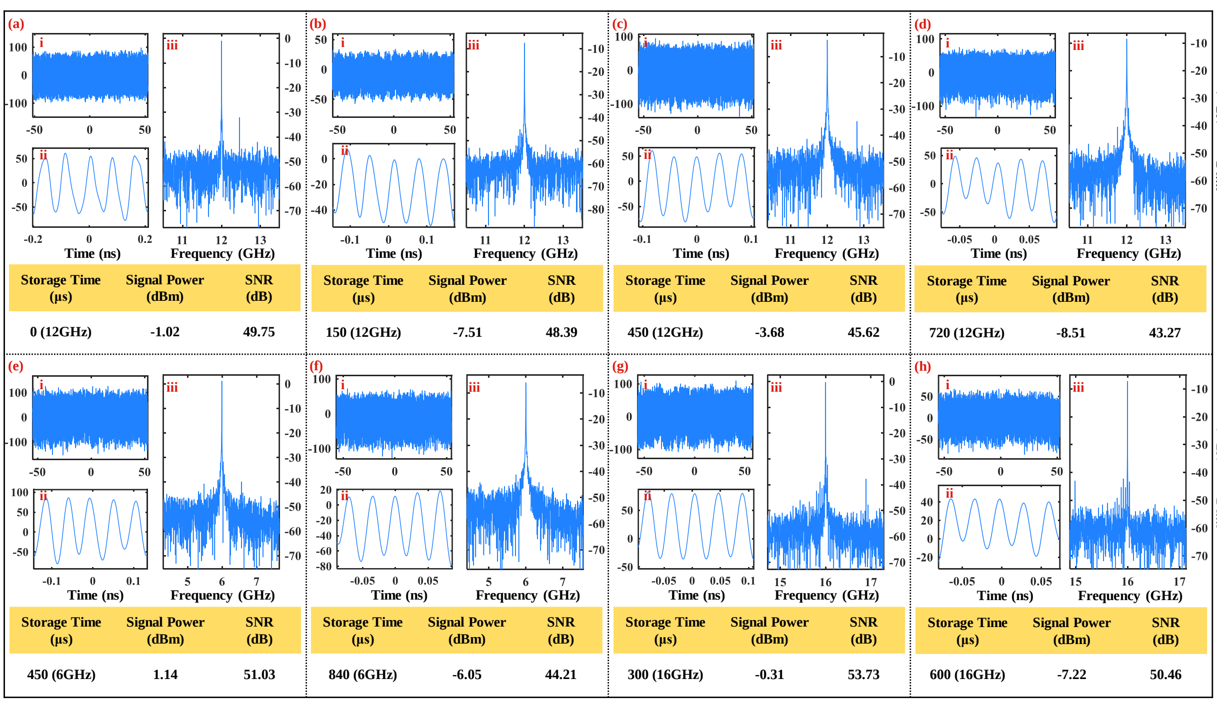

Fig. 2. The measured waveforms and spectra of the stored RF signal after different circulations. (a) The 12 GHz signal injected into the loop. (b) The 12 GHz signal stored for 150 μs (100 circulations). (c) The 12 GHz signal stored for 450 μs (300 circulations). (d) The 12 GHz signal stored for 720 μs (480 circulations). (e) The 6 GHz signal stored for 450 μs (300 circulations). (f) The 6 GHz signal stored for 840 μs (560 circulations). (g) The 16 GHz signal stored for 300 μs (200 circulations). (h) The 16 GHz signal stored for 600 μs (400 circulations). [i] Partial waveforms of the signals. [ii] Waveform details of the signals. [iii] Spectra of the signals.

The RF signal storage performance of our proposed scheme has been experimentally proven. The length of the optical fiber in the experiments was set to 300 m with a delay of 1.5 μs, and the frequencies of the RF signals were configured as 6 GHz, 12 GHz, and 16 GHz respectively for proof of concept. Fig. 2 presents the measured waveforms and spectra of the stored RF signal after different circulations via a digital storage oscilloscope (DSO). Here a frequency recovery algorithm was applied to remove the influence of AOM frequency shift in the spectra of Fig. 2(iii), and this method was followed in the subsequent experiments. For a 12 GHz signal, the signal power and SNR are -1.02 dBm and 49.75 dB when injected into the loop, respectively. After storage of 720 μs, corresponding to 480 circulations, the output signal power and SNR become -8.51 dBm and 43.27 dB, respectively, with an SNR degradation of only 6.48 dB, as shown in Fig. 2(a-d). The detailed changes in power and SNR of the stored 12 GHz signal are presented in Fig. 3(a). Throughout the storage process, the signal power is generally stable with an unnoticeable increase in noise level. Additionally, for an 8 GHz and a 16 GHz signal, the experimental results also show similarly great storage performance. The signals are allowed to be stored for 840 μs and 600 μs, corresponding to 560 and 400 circulations, respectively, with little additional SNR deterioration, as shown in Fig. 2(e-h).

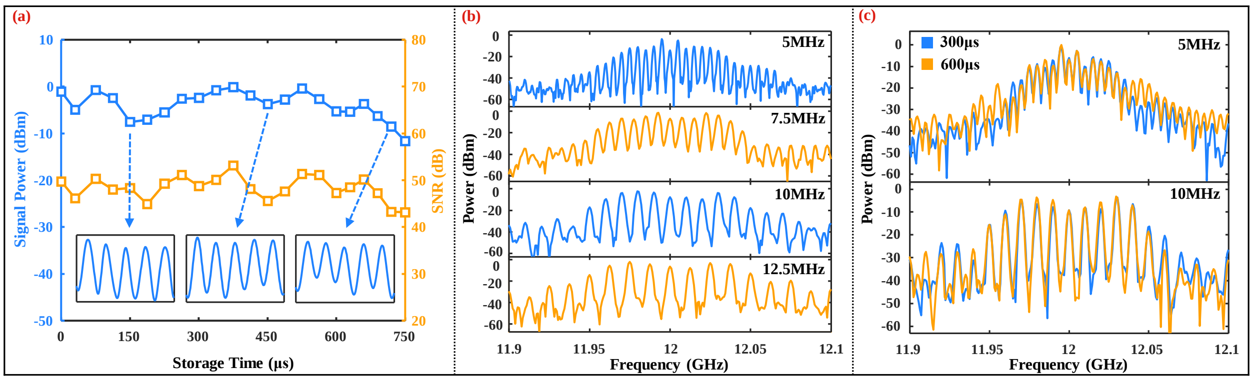

Fig. 3. (a) Power and SNR changes of the 12 GHz signal during storage. (b) The beat signal spectra of the Doppler-frequency modulated carriers and the RF-modulated signal before storage, with the Doppler frequencies of 5, 7.5, 10, and 12.5 MHz. (c) The beat signal spectra of the Doppler-frequency modulated carriers and the RF-modulated signal after 300 μs and 600 μs storage, with the Doppler frequencies of 5 and 10 MHz.

Next, the feasibility of our proposed scheme for generating multiple Doppler false targets has also been experimentally proven. The frequency of the RF signal was configured as 12 GHz, and the frequencies of the Doppler signals injected into the MZM and PM were set to 5, 7.5, 10, and 12.5 MHz, respectively, for optical carrier modulation. Fig. 3(b) shows the beat signal spectra of the Doppler-frequency modulated carriers and the RF-modulated signal before storage. It can be seen that these spectra not only contain the initial RF component but also generate many coherent copies with Doppler frequency shifts, containing different velocity false target deception information, forming a frequency comb structure. Furthermore, the simultaneous implementation of storage and deception functions was also measured. Fig. 3(c) shows the beat signal spectra of the Doppler-frequency modulated carriers and the RF-modulated signal after 300 μs and 600 μs storage. Apparently, the long storage hardly affects the fidelity of the generated frequency comb signals, and the SNR is still close to 40 dB, with more than 10 false targets consistently. Therefore, these high-quality coherent comb false target signals can be combined to perform range-velocity compound deception radar jamming with significantly improved jamming capability.

4. Conclusion

In conclusion, we proposed and demonstrated a frequency-comb-enabled PRFM and multi-false-target radar jamming method. In the experiments, More than 10 high-fidelity coherent false targets with different range-velocity deception information have been achieved in the all-optical domain for the first time. Thanks to the independent storage of the signal, the storage time has exceeded 840 μs with an SNR degradation of less than 10 dB, and the signal frequency has reached 16 GHz. The proposed system has optimized storage and jamming characteristics and is expected to facilitate the promotion and upgrade of PRFM in electronic countermeasures.

5. Acknowledge

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6. References

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