Compressive Sensing Chaos Radar Based on Self-Phase-modulated Feedback Semiconductor Laser Cascaded With Dispersive Component

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***Abstract*—We propose a compressive sensing chaos radar based on a self-phase-modulated feedback semiconductor laser cascaded with a dispersive component, and numerically demonstrate that the chaos radar achieves high imaging quality in a sparse scene.**

Keywords—chaos, semiconductor laser, compressive sensing, radar imaging

I. Introduction

High-resolution imaging radars [1-5] have substantial applications in both military and civilian domains. The deployment of ultra-wideband waveforms and large aperture arrays has significantly improved the resolution of radar imaging. However, high-rate analog-to-digital converters (ADCs) and the accompanying massive data processing have resulted in a significant increase in the cost of these systems. In 2007, Baraniuk et al. published a seminal paper [6] that applied the compressive sensing theory [7] to radar imaging. This approach replaced the conventional high-rate ADCs at the receivers, thus reducing the cost of hardware in radar systems.

Despite the promise of compressive sensing theory in reducing the cost of hardware in radar imaging systems, the research remains limited in this area. The problem of conventional compressive sensing radars is the requirement for random sub-sampling [8] to satisfy the restricted isometry property (RIP). This leads to the high cost of hardware for storage and computation. To mitigate this issue, some studies have proposed the use of noise signals as the transmission waveforms [9], allowing for sub-Nyquist sampling at the receiver to satisfy the RIP.

However, the generation and amplification of broadband noise signals are challenging. In this paper, we propose a solution to this issue by introducing a compressive sensing radar based on a self-phase-modulated feedback semiconductor laser cascaded with a dispersive component. This design reduces the cost of hardware compared with traditional compressive sensing radar systems.

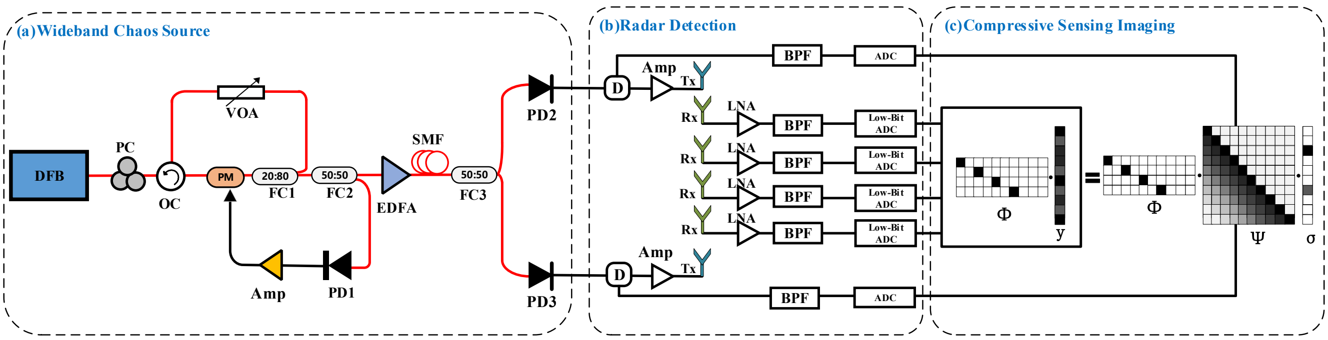

Fig. 1. System architecture for the proposed compressive sensing chaos radar. DFB, distributed-feedback laser; PM, phase modulator; OC, optical circulator; PC, polarization controller; FC, fiber coupler; PD, photodetector; Amp, radio-frequency amplifier; EDFA, erbium-doped fiber amplifier; VOA, variable optical attenuator; SMF, single-mode fiber; D, power divider; Tx, transmitter antenna; Rx, receiver antenna; LNA, low-noise amplifier; BPF, band-pass filter; ADC, analog to digital converter.

II. NUMERICAL MODEL

Fig. 1 shows the system architecture of the proposed compressive sensing radar. The system is comprised of three main components: the laser chaos source module, the radar detection module, and the compressive sensing imaging module. The output light of a distributed feedback (DFB) laser is modulated by a phase modulator. A polarization controller (PC) is used to match the polarization state of feedback light to that of the laser. The phase-modulated light is then split by a 20/80 fiber coupler (FC1). The 20% portion is fed back into the DFB laser, and the feedback strength is tuned by a variable optical attenuator (VOA). While the 80% portion of the phase-modulated signal is equally split into two beams by a 50/50 optical coupler (FC2). One beam of light is photon-detected by a photodetector (PD1) and then used as the driving signal of the phase modulator after being amplified by an RF amplifier, while the other beam of light is propagated through a dispersion component. The intrinsic parameters are set to typical values for a semiconductor laser [10].

The flat, wideband chaos with suppressed time delay signature is split into two beams by FC3 and converted into electrical signals by PD2 and PD3. A power splitter (D) divides the signals into two paths. One path is amplified by a radio frequency amplifier (Amp) and transmitted into the environment through the transmit antenna (Tx). The other path serves as the reference signal and is sent to the compressive sensing imaging module. The received signal, captured by the receive antenna (Rx), is processed by a low-noise amplifier (LNA) and a bandpass filter (BPF) before being sampled and transmitted to the compressive sensing imaging module by a low-bit ADC. In the numerical simulation, a multiple-input multiple-output (MIMO) array with two transmitters and four receivers was employed to demonstrate the imaging capabilities of the proposed chaos radar. The frequency range of the transmit antennas was set to 0.25GHz to 3GHz, and bandpass filters with a range of 0.25GHz to 1.75GHz were used. The simulation of the propagation of electromagnetic waves in free space was performed using the finite difference time domain (FDTD) method. The overall simulation process was sampled at a rate of 20GSamples/s, which was consistent with the FDTD cell size. The receiver was sampled at a rate of 1GSamples/s, which was 5% of the transmitter's A/D rate. The target for radar detection is a cylindrical object with a diameter of 0.1m.

In conventional MIMO radars, the orthogonality of the transmitted waveform is a crucial factor for the proper operation of the system. However, it is challenging to obtain ideal orthogonal waveforms in practice. In contrast, compressive sensing radar imaging systems do not require the orthogonality of the transmitted waveform and can still reconstruct sparse target scenes [11] even when transmitting non-orthogonal waveforms, which greatly simplifies the system design.

The compressive sensing imaging module processes the sampled data of the reference signal and echo signal. Radar imaging is transformed into a compressive sensing problem, and is solved through convex optimization or greedy algorithms to restore the imaging target scenario.

III. RESULTS AND ANALYSES

Fig. 2 illustrates the time-domain waveforms, spectra, and autocorrelation functions of COF and SPMOF+SMF. Both of the time-domain waveforms present noise-like characteristics, which allow for sub-Nyquist sampling to meet the RIP conditions of compressive sensing theory. However, due to the feedback light of COF being the delayed replica of the output, the output chaos has an intrinsic regularity, leading to less satisfaction with the RIP conditions, while the chaos generated by the SPMOF+SMF scheme is more random, making it easier to satisfy the RIP conditions. The radar transmission waveform bandwidth used in this paper is typically lower than 5GHz, so only the low-frequency spectral characteristics are observed. The chaos spectrum generated by the SPMOF+SMF scheme is flatter and closer to the white noise level, making it more suitable for compressive sensing.

Fig. 3 shows the results of traditional radar imaging algorithms and compressive sensing radar imaging. Fig. 3(a) to Fig. 3(d) are the ranging results, which show that the compressive sensing method reached a level similar to matched filtering with only 5% of the samples. Fig. 3(e) to Fig. 3(h) are the imaging detection results, which respectively use the back projection imaging and compressive sensing imaging to image single and double target scenarios. In Fig. 3(g) and Fig. 3(h), the imaging results produced by back projection are noticeably broadened in the direction position, leading to misjudgments of the target's volume and shape. Meanwhile, strong scattering from the target may result in the loss of weak scattering targets. In Fig. 3(e) and Fig. 3(f), the imaging results obtained from compressive sensing are similar in size and shape to the actual targets, and there is no sidelobe.

Compressive sensing imaging has two main advantages over back projection imaging: Firstly, the compressive sensing algorithm only requires 5% of the samples to image sparse target scenarios, reducing the cost of the receiver hardware and the amount of data that needs to be stored.

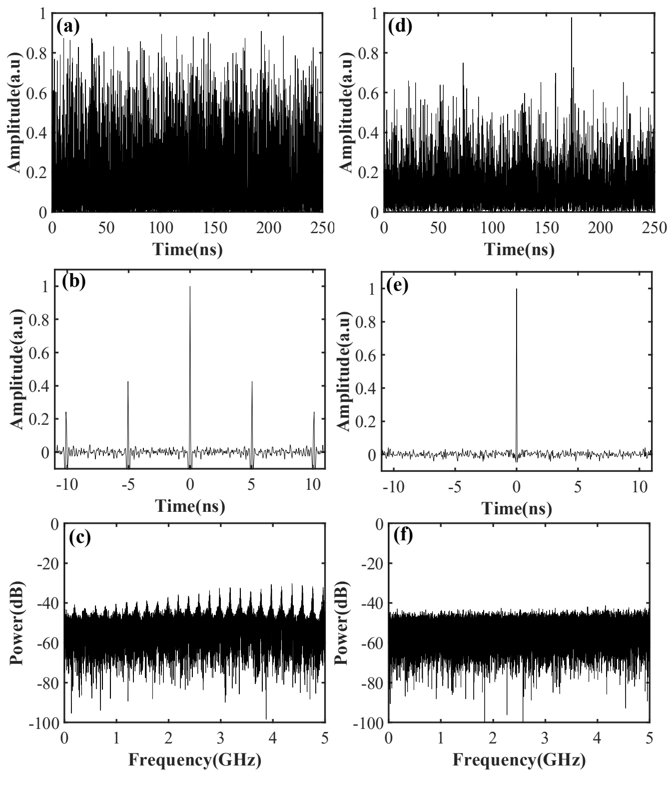

Fig. 2. Numerical temporal intensity waveforms (first row), autocorrelation function (second row) and RF spectra (third row) of chaos generated by (a)-(c) COF and (d)-(f) SPMOF+SMF. The feedback strength is fixed at -20dB.

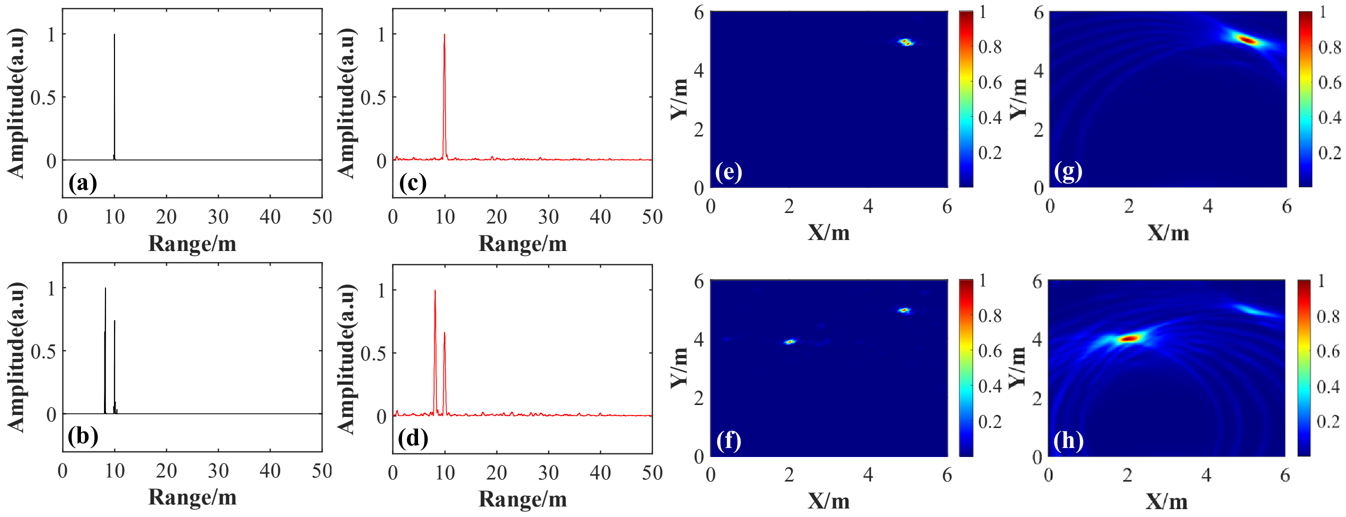

Fig. 3. Ranging results (the first and second columns) and imaging results (the third and fourth columns) processed by (a), (b), (e), (f) compressive sensing (CS) and (c), (d), (g), (h) matched filtering (MF) and back projection (BP).

Secondly, the reconstructed image from compressive sensing does not have sidelobes, avoiding the masking of weak scattering targets by strong scattering targets, while sidelobes are evident in the images from back projection imaging. It is worth mentioning that the microwave chaos used in this paper as the transmit waveform can satisfy the RIP conditions of compressive sensing theory by using uniform subsampling. This work makes compressive sensing radar more feasible in practical applications.

IV. Conclusion

In this paper, we propose a chaos radar based on compressive sensing for ranging and imaging in sparse scenes. Compressive sensing radar can reduce hardware costs by using low-rate A/D and has better imaging quality by reducing sidelobe interference compared to traditional radar imaging. Using a laser chaotic source as the signal source for compressive sensing radar eliminates the hardware cost for random sampling in conventional compressive sensing radar systems, and wideband laser chaotic signals are easier to obtain than wideband thermal noise signals. Numerical simulation results show that the proposed compressive sensing radar system can reconstruct sparse target scenes with a small number of samples. This work helps in the hardware implementation of compressive sensing radar and has the potential to build a high-resolution radar imaging system at a low cost.

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