An Integrated Radar Detection and Microwave Frequency Measurement System Based on an Optically Injected Semiconductor Laser

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Abstract: An integrated radar detection and microwave frequency measurement system has been proposed and experimentally demonstrated based on an optically injected semiconductor laser. Both high-resolution radar detection and accurate microwave frequency measurement are realized simultaneously. © 2023 The Author(s)
OCIS codes: (140.5960) Semiconductor lasers; (060.5625) Radio frequency photonics; (280.5600) Radar.

1. Introduction

As three desirable functions in modern military applications, radar, electronic warfare, and communication have attracted much attention. By implementing multiple functions through an integrated system, the cost and volume of the hardware platform can be greatly reduced [1],[2]. In electronic warfare systems, fast and broadband frequency measurement (FM) of the intercepted signal from radar and communication systems is of critical importance. There have been a number of photonics-based microwave frequency measurement approaches, which can be divided into three main categories, i.e., frequency-to-power mapping, frequency-to-space mapping, and frequency-to-time mapping [1]-[3]. Among these approaches, the frequency-to-time mapping scheme is considered a promising candidate for accurate multi-frequency measurement, and the measurement range is determined by the bandwidth of the linear frequency-modulated (LFM) signal. Compared with traditional radar schemes, photonics-based radars exhibit unique advantages in high frequency and large bandwidth [4]-[6]. Therefore, photonics-based radars can achieve a higher range resolution and processing speed. Among the photonics-based radar schemes proposed in recent years, microwave photonic frequency multiplication is a major method for broadband radar signal generation [5]. However, an external LFM signal is necessary, which inevitably increases the cost and restricts the reconfigurable capabilities. Alternatively, broadband radar transmit signal generation can be realized using an optically injected semiconductor laser (OISL) [6]-[8]. By simply controlling the detuning frequency and/or the injection strength of the OISL, a desired LFM signal can be produced. Since no external radio-frequency (RF) source is needed, this method can achieve a large bandwidth as well as flexible frequency tunability at low cost.

In this report, we put forward an integrated radar detection and microwave frequency measurement system based on an OISL. The two functions are combined by sharing a broadband dual-chirp LFM signal, which is provided by the OISL module. After that, photonic microwave mixing is carried out in the two orthogonal polarizations to implement radar detection and frequency measurement simultaneously. A range resolution as high as 1.25 cm and a measurement error within ±50 MHz are achieved in radar detection and frequency measurement, respectively. The proposed dual-functional system features compactness, low cost and increased flexibility, which may have enormous potential in the field of radar and electronic warfare.

2. Principle and experimental demonstration

Figure 1 depicts the schematic diagram of the proposed integrated system for radar detection and microwave frequency measurement. An optical carrier from the master laser (ML) is modulated by an electrical drive signal $V(t)$ at a Mach–Zehnder modulator (MZM) before being injected into the slave laser (SL) via an optical circulator (CIR). A variable optical attenuator (VOA) is inserted to adjust the optical injection strength, while the master-slave detuning frequency can be changed by tuning the output frequency of the ML. By setting an appropriate detuning frequency and injection strength, the SL can operate in the period-one (P1) oscillation state, and the P1 oscillation frequency is widely tunable. By properly setting $V(t)$ to have a triangular-like profile, a dual-chirp LFM signal can be obtained after the photodetector (PD1) [6]. An electrical power divider (Div) splits the amplified LFM signal into two parts. One part is launched into air via a transmitting antenna (Tx) to detect the target. The other part is used as a reference signal to drive both sub-MZMs, i.e., X-MZM and Y-MZM, of a dual-polarization MZM (Dpol-MZM). In the X-MZM, the optical carrier is modulated by the reference signal and the radar echo that is reflected by the target and collected by a receiving antenna (Rx). At the same time, the reference signal and the signal under test (SUT) are applied to drive the optical carrier at the Y-MZM. At the optical output of the Dpol-DMZM, a polarization beam splitter (PBS) is followed to separate the optical signals in the orthogonal polarizations, denoted as X-pol and Y-pol. The obtained signal in X-pol is used for radar detection, and is sent to a PD (PD2) to perform photonic frequency mixing. After PD2, an electrical lowpass filter (ELPF) is employed to select the de-chirped low-frequency component. Subsequently, the de-chirped signal is sampled by a low-speed analog-to-digital converting (ADC) unit and analyzed by a digital signal processing (DSP) unit to acquire the range information of targets. Meanwhile, the separated optical signal in the Y-pol is directed to another PD (PD3) for optical-to-electrical conversion. Following PD3, the output signal passes through a narrow-band electrical bandpass filter (EBPF) and an envelope detector (ED) to complete the procedure of frequency-to-time mapping [3]. In this case, with the aid of the ADC unit, a pair of electrical pulses can be measured in a single period, and the time interval between the adjacent pulses is directly proportional to the unknown frequency of the SUT. Therefore, by simply measuring the time intervals, microwave frequency measurement is achievable in the proposed system.

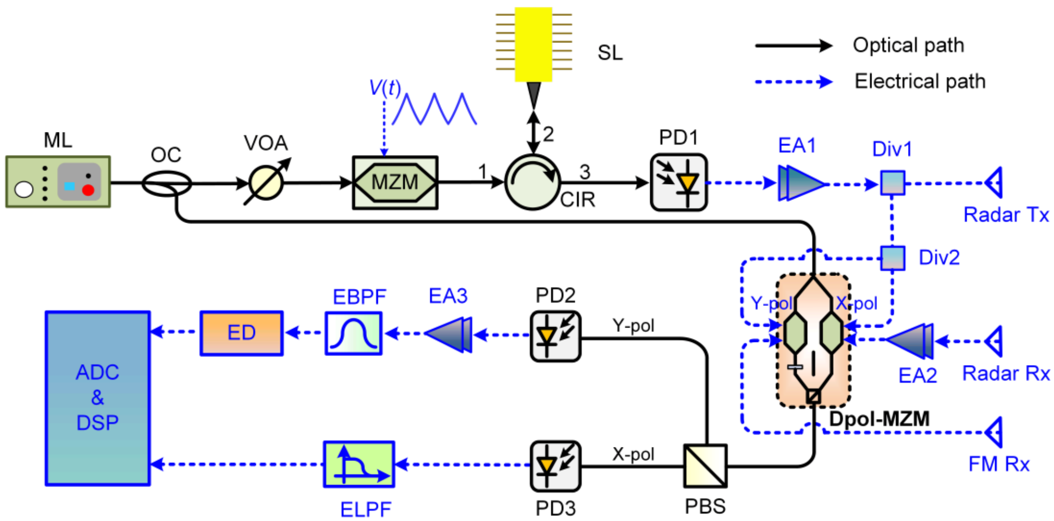

Fig. 1. Schematic diagram of the proposed integrated system for radar detection and frequency measurement.

An experiment is performed based on the setup in Fig. 1. The master-slave detuning frequency and injection power are set to (2 GHz, -3.77 dBm), a P1 oscillation state is excited with an oscillation frequency of 18.6 GHz. Figure 2(a) provides the optical spectra of the ML (red), the free-running SL (green), and the injected SL (blue). As plotted in Fig. 2(b), the control signal $V(t)$ has an amplitude of 0.702 V and a period of 10 µs. As a consequence, the temporal waveform of the resultant LFM signal is obtained at the output of PD1, as shown in Fig. 2(c). The instantaneous frequency-time diagram is obtained using the short-time Fourier transform. As shown in Fig. 2(d), the generated dual-chirp LFM signal has a bandwidth of 6 GHz (from 12 to 18 GHz) and a temporal period of 10 µs.

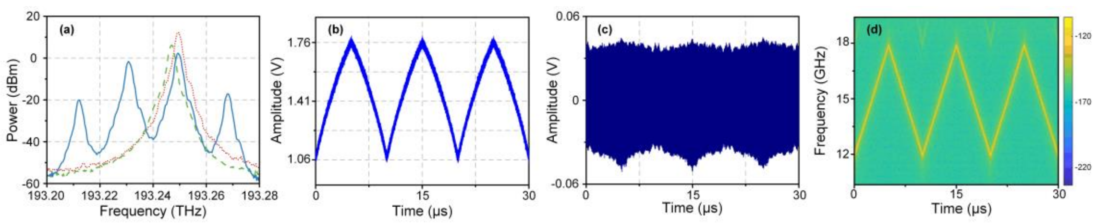

Fig. 2. (a) Optical spectra of the ML, the free-running SL, and the injected SL, (b) control signal $V(t)$, (c) temporal waveform of the LFM signal, and (d) instantaneous frequency-time diagram.

To test the performance of radar detection, an aluminum trihedral corner reflector (TCR) is first applied for single-target detection, which is located 26 cm away from the antenna pair. The electrical spectrum of the de-chirped signal is obtained by performing a fast Fourier transform (FFT) on the captured waveforms. As observed in Fig. 3(a), the spectral peak appears at 25.45 cm, which is close to the real value. The 3-dB width of the main peak is calculated to be 1.25 cm, which is consistent with the theoretical range resolution. To illustrate the multi-target detection capability, two TCRs are placed 25.50 cm apart. As shown in Fig. 3(b), two dominant peaks can be easily distinguished. Furthermore, an inverse synthetic aperture radar (ISAR) imaging experiment is demonstrated, and the target is a triangle composed of six TCRs, which are placed on a rotating platform. Figure 3(c) shows the obtained ISAR image by executing a Range-Doppler (RD) algorithm on the de-chirped signal [6]. In Fig. 3(c), all the TCRs can be clearly distinguished, and the measured distance agrees well with the real value.

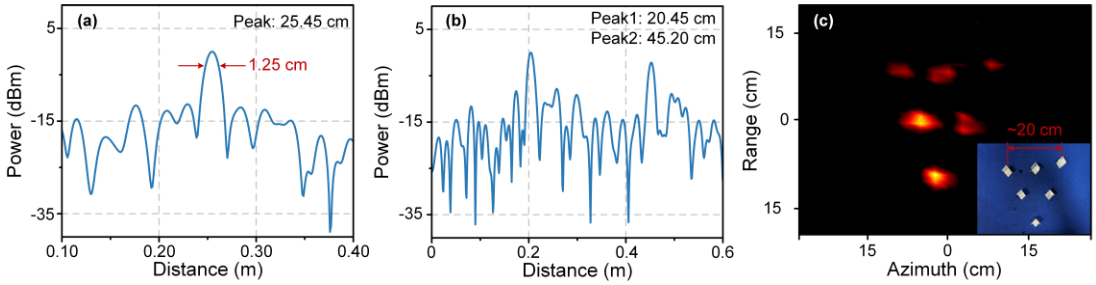

Fig. 3. Radar detection results for (a) a single target and (b) two targets; and (c) ISAR imaging.

For microwave frequency measurement, a single-tone SUT of 4 GHz is measured and a pair of pulses with a 6.69-μs time interval are recorded in Fig. 4(a). According to the linear frequency-to-time relationship between the pulse interval and the input frequency, the SUT frequency is calculated to be 4.010 GHz, leading to a minor error of only 10 MHz. To further illustrate the frequency measurement resolution, a two-tone microwave signal with a 20-MHz frequency difference, e.g., 6 GHz and 6.02 GHz, is used as the SUT. As shown in Fig. 4(b), the two adjacent pulses in the signal acquired by the ADC can still be clearly identified. This implies that the frequency resolution of the proposed frequency measurement system reaches 20 MHz, which is determined by the 20-MHz bandwidth of the adopted EBPF (center frequency 9.95 GHz). In addition, the frequency measurement range can be extended by tuning the frequency coverage of the generated LFM signal [7]. The frequency coverage of the LFM signal generated via an OISL is flexibly tuned to 10–20 GHz or 20–30 GHz by varying the injection parameters and/or the control signal $V(t)$. As a consequence, the frequency measurement range is enlarged to 0.05–39.95 GHz. Figure 4(c) presents the measured frequency results when the input frequency varies from 1 GHz to 39 GHz with a step of 1 GHz, and the measurement errors are kept below ±50 MHz.

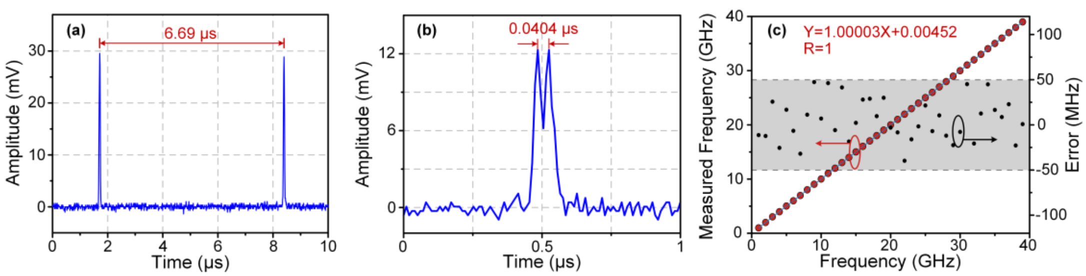

Fig. 4. Frequency measurement results for (a) a single-tone signal, (b) a two-tone signal, and (c) a tunable signal from 1 GHz to 39 GHz.

3. Conclusions

In conclusion, we have proposed and experimentally demonstrated an integrated system for radar detection and frequency measurement. By taking advantage of an optically injected semiconductor laser for broadband LFM signal generation and a Dpol-MZM for polarization-division multiplexing, both high-resolution radar detection and accurate microwave frequency measurement are realized in a single system. A range resolution as high as 1.25 cm and a measurement error within ±50 MHz are achieved in radar detection and frequency measurement, respectively. The experimental results confirm that the proposed scheme is a promising solution for future RF systems with multiple functions.

This work was supported by the NSFC Program (62001317, 62004135, 62171305); and the NSFC Program of Jiangsu Province (BK20200855); and the Natural Science Research Project of Jiangsu Higher Education Institutions (20KJB510011, 20KJA416001).

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