Dual-Chirp Microwave Waveform Generation by a Dual-Beam Optically injected Semiconductor Laser

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Abstract: We propose an approach to generating dual-chirp microwave waveforms based on a dual-beam optically injected semiconductor laser. Tunable dual-chirp microwave waveforms with a large time-bandwidth product are experimentally generated.
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1. Introduction

Thanks to the pulse compression ability, a linearly chirped microwave waveform (LCMW) has been considered as one of the most commonly-used radar waveforms to achieve both a large detection range and a high range resolution. However, with a knife-edge type ambiguity function, an LCMW has severe range-doppler coupling, resulting in a poor two-dimension united resolution of range and velocity. To cope with this problem, dual-chirp microwave waveforms (DCMWs) have been introduced. A DCMW consists of two complementary chirped components within the same temporal period, one up-chirped and the other down-chirped. With an optimal (thumb-type) ambiguity function, a DCMW is very promising in reducing the range-doppler coupling and improving the range-velocity resolution. In general, the DCMW generation by purely electrical techniques suffers from the limited frequency and bandwidth. Therefore, many photonic-based approaches have been proposed to generate these waveforms with a high carrier frequency and large bandwidth. One major method relies on a baseband single-chirp waveform as well as a high-order electro-optic modulator, such as a dual-parallel Mach-Zehnder modulator (DP-MZM) [1] or a dual-polarization quadrature phase shift keying (DP-QPSK) modulator [2]. The main drawback is its high cost and complex structure which usually requires a wideband microwave arbitrary waveform generator (AWG) and a high-speed modulator.

Recently, photonic generation of microwave waveforms has received considerable attention, where the rich dynamics of optically injected semiconductor lasers has been explored and their period-one (P1) oscillations have been widely used [3,4]. For instance, by properly varying the injection parameters, the P1 frequency can be tuned from a few to over 100 GHz. In [5], we proposed and experimentally demonstrated a novel scheme to generate LCMWs with a large time-bandwidth product (TBWP) by simply controlling the injection strength of an optically injected semiconductor laser.

In this report, the generation of interesting DCMWs is presented by incorporating a dual-beam optically injected semiconductor laser. By taking advantages of the nonlinear dynamics of dual-beam injection and injection strength controlling, tunable DCMWs with a large TBWP can be obtained. The proposed method requires no high-speed modulator or AWG, thus featuring low cost, simple structure, which may be promising in modern radar systems.

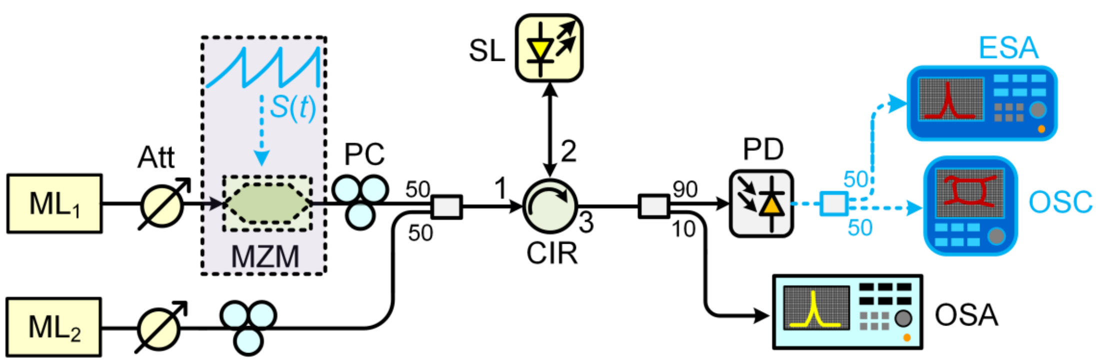

Fig. 1. Block diagram of the experimental set-up. ML: master laser, Att: optical attenuator, PC: polarization controller, MZM: Mach-Zehnder modulator, $S(t)$: control signal, CIR: optical circulator, SL: slave laser, PD: photodetector, OSA: optical spectral analyzer, ESA: electrical spectral analyzer, OSC: oscilloscope.

2. Experimental setup and results

Figure 1 depicts the experimental set-up used for the DCMW generation. A commercial distributed-feedback semiconductor laser (Actech LD15DM) is applied as the slave laser (SL). Under a bias current of 31.7 mA and a stabilized temperature of 24.2 °C, the free-running frequency and power of the SL are 194.06 THz and 3.63 dBm, respectively. Two optical carriers (ML_1 and ML_2) from a multi-channel laser source (Agilent N7714A) are optically injected into the SL, which are detuned by f_1 and f_2 from the free-running frequency of the SL. An optical attenuator and a polarization controller are included after ML_1 and ML_2 to control the optical injection power and polarization. The light of both MLs is combined together through a 50/50 coupler and then injected into the SL through an optical circulator (CIR). At the third port of the CIR, the SL output is sent to a 30-GHz photodetector (PD) for optical-to-electrical conversion. Then the electrical properties of the generated microwave signal are analyzed in an 80-GSa/s real-time oscilloscope (OSC, Keysight DSO-X 92504A) and an electrical spectral analyzer (ESA, R&S FSV 40). The optical spectrum is monitored in an optical spectral analyzer (OSA, Yokogawa AQ6370C).

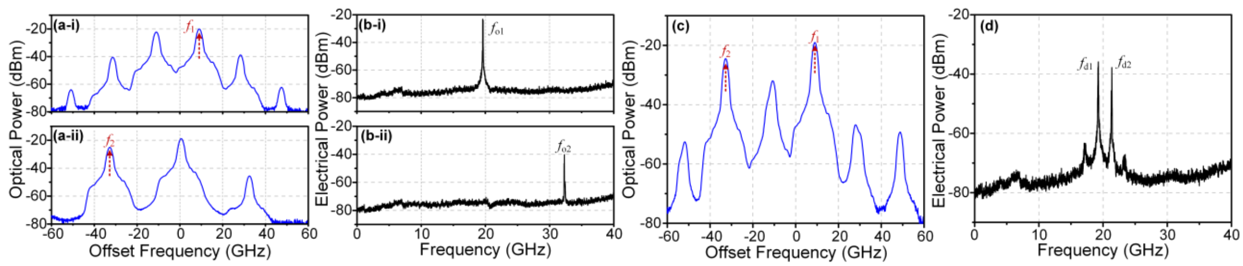

Fig. 2. Optical (a & c) and electrical (b & d) spectra of the SL subject to single-beam (a & b) and dual-beam (c & d) injection.

Firstly, the frequency detuning and injection strength of ML1 (f_1, ξ_1) are set to be (9.1 GHz, 0.55). In this study, the injection strength is defined as the square root of the power ratio between the injected optical signal and output of the free-running SL. Under these circumstances, a P1 oscillation state is excited with a fundamental frequency of f_{o1} = 19.3 GHz. The optical and electrical spectra of the SL subject to single-beam injection from ML_1 are illustrated in Fig. 2(a-i) and 2(b-i), respectively. Likewise, the results for the single-beam injection from ML_2 are presented in Fig. 2(a-ii) and 2(b-ii), where the single-beam injection of (f_2, ξ_2) = (-32.8 GHz, 0.49) also induces a P1 oscillation with f_{o2} = 32.3 GHz. When both beams are simultaneously injected, the SL operates in the so-called Scenario B of dual-beam injection according to [6], where the nonlinear dynamics by f_1 single-beam injection is preserved while that of f_2 single-beam injection is suppressed. As can be seen in the optical spectrum of Fig. 2(c), the P1 dynamics of f_1 single-beam injection is dominant, while f_2 injection beam modifies the f_1 injection induced dynamics through nonlinear mixing. At the output of the PD, two major frequency components (f_{d1}, f_{d2}) = (19.3 GHz, 21.3 GHz) are observed in the electrical spectrum of Fig. 2(d). Their frequencies meet the conditions of $f_{d1} \approx f_{o1}$ and $f_{d2} \approx f_1 - f_2 - f_{d1}$. Note that the frequency component of $f_1 - f_2$ has been blocked due to the limited bandwidth of the PD.

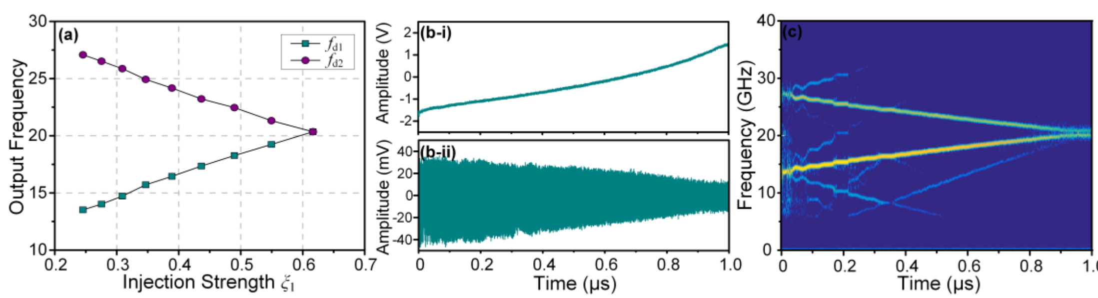

Fig. 3. (a) Frequencies of the generated microwave signals as a function of ML_1's injection strength, (b) measured waveform of the control signal (i) and the generated DCMW (ii) with one period, and (c) instantaneous frequency-time diagram.

It has been proved that for a fixed master-slave detuning, the P1 oscillation frequency would increase approximately linearly with the injection strength [4]. Thus, when positive f_1 and negative f_2 are fixed, frequencies of the generated two microwave signals (f_{d1}, f_{d2}) will increase and decrease monotonously with the ML_1's injection strength ξ_1, respectively. Typical results of this phenomenon are displayed in Fig. 3(a), which are consistent with our expectation. In order to generate DCMWs, the system has incorporated an injection strength controller which contains a 10-Gb/s MZM and an electrical control signal $S(t)$ from a 120-MHz AWG (Agilent 81150A). As plotted in Fig. 3(b-i), the profile of $S(t)$ is mainly designed to compensate for the nonlinearity of the amplitude transfer function of the MZM [5]. As a consequence, ML_1's injection strength would increase linearly in a temporal period. The resultant instantaneous frequencies of f_{d1} and f_{d2} would correspondingly increase and decrease linearly. In other words, a DCMW has been generated, and its temporal waveform is shown in Fig. 3(b-ii). In Fig. 3(c), an instantaneous frequency-time diagram of the generated DCMW is calculated using the short-time Fourier transform. As can be seen, the generated waveform contains both an up-chirp (13.4 – 20.2 GHz) and a down-chirp (27.3 – 20.5 GHz) waveform in the same 1-µs period, corresponding to a large TBWP of 6800.

Frequency tunability of the generated DCMWs could be achieved by adjusting the frequency detuning and injection strength of both MLs as long as the SL is kept in Scenario B of dual-beam injection. For instance, Fig. 4 provides instantaneous frequency-time diagrams of the generated DCMWs with different frequency coverage. In Fig. 4(a), the generated signal has a frequency coverage of (25.8 – 30.0 GHz) and (25.8 – 21.6 GHz). In Fig. 4(b), the frequency range has been moved to (25.5 – 28.0 GHz) and (17.2 – 14.7 GHz). Likewise, Fig. 4(c) corresponds to the case of a DCMW covering (30.0 – 26.0 GHz) and (15.2 – 19.2 GHz).

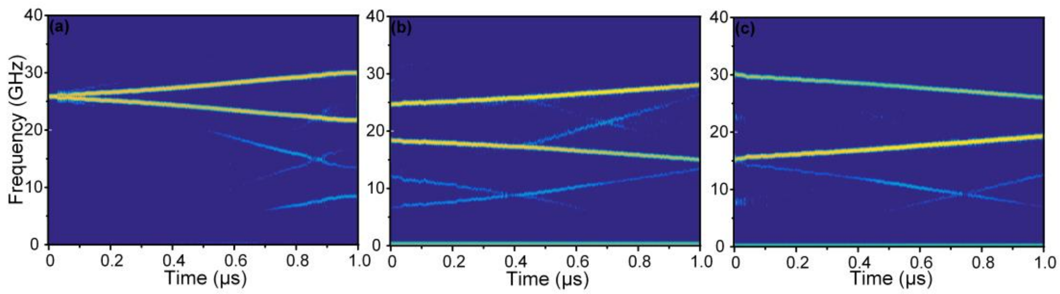

Fig. 4. Instantaneous frequency-time diagrams of the generated DCMWs with different frequency coverages.

3. Conclusions

To the best of our knowledge, this is the first demonstration of DCMW generation based on a dual-beam optically injected semiconductor laser. By taking advantages of the nonlinear dynamics of dual-beam injection and injection strength controlling, tunable DCMWs with a large TBWP can be generated. In the experimental demonstration, a DCMW in a temporal period of 1 µs has been obtained, which offers an up-chirp (13.4 – 20.2 GHz) and a down-chirp (27.3 – 20.5 GHz). Besides, frequency tunability of the generated waveform has been realized by simply adjusting the injection parameters (frequency detuning and injection strength). Without using any high-speed modulator or AWG, the proposed technique features low cost, simple structure, and, thus, may find wide applications in modern radar systems.

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4. References

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