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Linearly chirped microwave waveform generation with large time-bandwidth product by optically injected semiconductor laser

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Abstract: A scheme for photonic generation of linearly chirped microwave waveforms (LCMWs) with a large time-bandwidth product (TBWP) is proposed and demonstrated based on an optically injected semiconductor laser. In the proposed system, the optically injected semiconductor laser is operated in period-one (P1) oscillation state. After optical-to-electrical conversion, a microwave signal can be generated with its frequency determined by the injection strength. By properly controlling the injection strength, an LCMW with a large TBWP can be generated. The proposed system has a simple and compact structure. Besides, the center frequency, bandwidth, as well as the temporal duration of the generated LCMWs can be easily adjusted. An experiment is carried out. LCMWs with TBWPs as large as 1.2×10^5 (bandwidth 12 GHz; temporal duration 10 μs) are successfully generated. The flexibility for tuning the center frequency, bandwidth and temporal duration is also demonstrated.

OCIS codes: (140.5960) Semiconductor lasers; (060.5625) Radio frequency photonics; (350.4010) Microwaves; (190.3100) Instabilities and chaos; (280.5600) Radar.

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1. Introduction

Linearly chirped microwave waveforms (LCMWs) have wide applications in modern radar systems, where LCMWs with a large time-bandwidth product (TBWP) are highly desired to simultaneously achieve a large detection range and a high range resolution [1, 2]. Conventionally, LCMWs are generated in electrical domain using a scanning microwave oscillator [3] or a direct digital synthesizer (DDS) [4]. Due to the limitations of current electronic circuits, the generated LCMWs usually have a low central frequency and a bandwidth less than a few gigahertz, which results in a small TBWP. While, in advanced radar systems, LCMWs with central frequency and bandwidth up to tens of gigahertz and TBWP over thousands are preferred. To deal with these problems, numerous photonic approaches have been proposed to generate LCMWs with the advantages of high frequency and large bandwidth [5–18]. Among all the schemes for photonic LCMW generation, one method is based on space-to-time mapping (STM) or frequency-to-time mapping (FTM) [5–10]. Microwave waveform generation based on STM is implemented by a spatial light modulator (SLM) for spatial shaping, which has flexibility in terms of waveform shape and central frequency [5–7]. However, due to the use of free-space optical devices, the system is complicated and suffers from large size and high coupling loss. Microwave waveform generation scheme based on FTM usually contains an optical spectral shaper and a dispersive element [8–10]. In such systems, the optical spectrum of a pulsed optical source is first modified by a spectral shaper, e.g., a fiber Bragg grating (FBG), before realizing FTM in the dispersive element. Nevertheless, the spectral response of the optical spectral shaper is usually fixed, resulting in waveforms that are either fixed or only slightly tunable. Besides, because of the limited spectral processing resolution (usually > several GHz), the temporal duration of the generated LCMW is typically several or tens of nanoseconds, leading to a small TBWP usually less than 100. The second method for photonic LCMW generation is realized by beating two coherent lights that have a quadratic phase difference between each other at a photo-detector (PD) [11–14]. The two lights can be spatially separated or orthogonally polarized, and the phase difference is imposed by applying a parabolic phase modulation. In these systems, the TBWP is mainly constrained by the limited modulation index of the applied electro-optical modulator (EOM), which is usually less than 10. By using a recirculating phase modulation loop [13] or a split parabolic driving electrical signal [14], the TBWP can be enlarged to some degree, but it is still hard to exceed 100 in both cases. Another drawback associated with this method is that, a high-speed microwave arbitrary waveform generator (AWG) is required to provide the electrical parabolic driving signal,

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which would increase the system complexity and cost. The third method for photonic LCMW generation is based on heterodyning of a linearly chirped optical pulse with a continuous wave (CW) light or another linearly chirped optical pulse with different chirp rate [15–17]. In these systems, a short optical pulse from a mode-locked laser is sent to a dispersive element, thus a quadratic phase profile would be imposed on the optical pulse. The dispersive element can be a dispersion compensation fiber, a single-mode fiber or a linearly chirped FBG. For this method, the small time aperture (usually several or tens of nanoseconds) is the major problem that limits the TBWP of the generated LCMW. In addition to the above photonic LCMW generation methods, an LCMW can also be generated by beating a wavelength sweeping distributed feedback (DFB) laser with another optical carrier at a PD [18, 19]. This method can generate LCMWs with a TBWP as large as $1.8\text{x}10^5$ [18], but suffers from a poor quality of generated LCMW because of the serious dynamic linewidth broadening of DFB laser during wavelength sweeping. Besides, the noncoherent phase relation between the two lasers would further degrade the signal quality after optical-to-electrical conversion.

In this paper, we propose the generation of LCMWs having large TBWP with a very simple and compact structure mainly incorporating an optically injected semiconductor laser. Based on the period-one (P1) dynamics of the optically injected semiconductor laser, a frequency-tunable microwave signal can be generated with its frequency determined by the injection strength. By properly controlling the injection strength, an LCMW with a large TBWP can be achieved. The central frequency, bandwidth and the temporal duration of the generated LCMW can be easily adjusted. In the experiment, the generated LCMWs can achieve a bandwidth of 12 GHz and a temporal period of 10 μs. The corresponding TBWP reaches as large as $1.2\text{x}10^5$, which is remarkably larger than most of the previously reported results. The feasibility of tuning the central frequency, bandwidth and temporal duration is also verified.

2. Operation principle

Figure 1(a) shows the schematic diagram of the proposed photonic LCMW generator. A CW light from a master laser (ML) with frequency f_m is injected to a slave laser (SL) through an optical circulator. The slave laser is a semiconductor laser with a free-running frequency f_s. Before the optical circulator, a polarization controller (PC) is used to align the polarization of the injection light with that of the slave laser to maximize the injection efficiency. To excite the P1 dynamics, the frequency of the injection light is detuned by f_i ($f_i = f_m - f_s$) from the free-running frequency of the slave laser. In addition, the power of injection light can be adjusted by a variable optical attenuator. After properly optical injection, the slave laser can operate at the P1 oscillation state, and two dominant wavelengths, i.e., a regenerated optical carrier with frequency f_m and a cavity mode with frequency f_s', can be generated at the output of the slave laser [20–22]. Since the optical injection reduces the necessary gain in the slave laser, the cavity mode with frequency f_s' in the slave laser will be red-shifted compared with the free-running frequency (f_s), according to the antiguidance effect [22]. When the output signal from the slave laser is sent to a PD, a microwave signal having frequency f_o ($f_o = f_m - f_s$') can be generated, and the frequency can be continuously tuned from a few to tens of gigahertz by changing the detuning frequency f_i and/or the injection strength [22]. Here, the injection strength is characterized by the injection parameter ξ, which is defined as the square root of the power ratio between the injected light and the free-running slave laser, i.e., the injection parameter ξ is proportional to the optical amplitude of the light injected to the slave laser. For a fixed master-slave detuning frequency f_i, the microwave frequency f_o would increase approximately linearly with the injection parameter over a large range [21, 22]. Therefore, when a control signal $S(t)$ is applied to an intensity modulator (IM) to manipulate the amplitude of the injection light before it is sent to the slave laser, the resultant microwave frequency f_o will be changed correspondingly. By setting the control signal $S(t)$ to have a near-sawtooth profile, the injected light can have a linearly increased optical amplitude, and the generated microwave signal would also have a linearly increased frequency, i.e., an LCMW is generated. In this process, the bandwidth of the LCMW can be enlarged by setting a large amplitude variation of the injection light, and the tuning speed can be properly slowed to achieve a large temporal duration. Therefore, it is possible to achieve a large TBWP. In addition, the central frequency of the LCMW can also be tuned by changing the initial injection parameter.

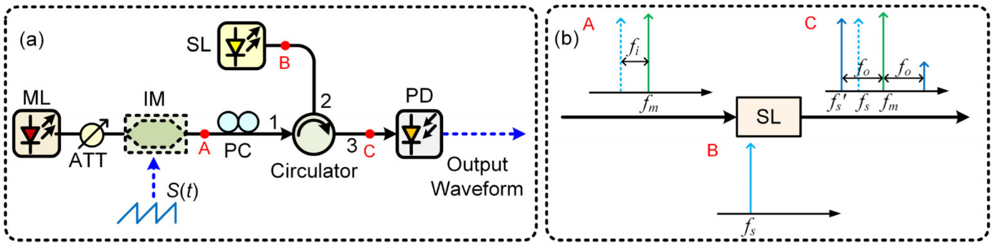

Fig. 1. (a) Schematic diagram and (b) illustration of the operation principle of the proposed photonic LCMW generator. ML: master laser, ATT: optical attenuator; IM: intensity modulator, PC: polarization controller, SL: slave laser, PD: photo-detector.

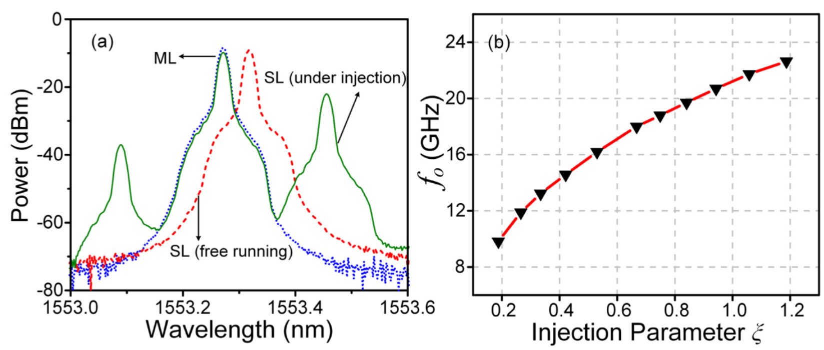

Fig. 2. (a) Optical spectra of the injection light (blue dot curve), free-running slave laser (red dashed curve) and the injected slave laser (ξ = 1.19, green solid curve), (b) measured output frequency as a function of the injection parameter.

3. Experimental demonstration

An experiment based on the setup in Fig. 1 is implemented. A laser source (Agilent N7714A) with a wavelength of 1553.272 nm and a power of 14.5 dBm is applied as the master laser. The CW light from the master laser is sent to a 10 Gb/s MZM. An electrical control signal generated by a 120-MHz arbitrary waveform generator (Agilent 81150A) is applied to the MZM to control the optical amplitude injected to the slave laser. The slave laser (Actech LD15DM) is a DFB laser biased at 31.7 mA, about 5 times of its threshold. Its free-running wavelength and power is 1553.318 nm and 5.48 dBm, respectively. Throughout the experiments reported in this paper, the master-slave detuning frequency is fixed at 5.7 GHz, unless otherwise specified. At the optical output, a PD (u2t XPDV2120RA) with a 40 GHz bandwidth is used to perform optical-to-electrical conversion. The generated LCMW is observed by an 80 GSa/s real-time oscilloscope (Keysight DSO-X 92504A). The optical spectrum is measured by an optical spectrum analyzer (Yokogawa AQ6370C).

First, the electrical control signal is not applied and the power of the CW light injected to the slave laser is adjusted by the optical attenuator. Figure 2(a) shows the optical spectra of the injection light (blue dot curve), the slave laser before (red dashed curve) and after (green solid curve) optical injection, when P1 oscillation state is excited and ξ equals to 1.19. As can be seen, two highly dominant wavelength components separated by the P1 oscillation

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frequency f_o is observed after optical injection. The oscillation frequency (f_o) as a function of the injection parameters ξ is also measured. In this process, the injection parameter is changed by tuning the optical power injected to the slave laser, and it can be calculated according to the injection power measured at the output port of the circulator connected to slave laser (port 2) and the optical power of the free running slave laser. As shown in Fig. 2(b), the oscillation frequency (f_o) increases almost linearly with the injection parameter ξ over a large frequency range.

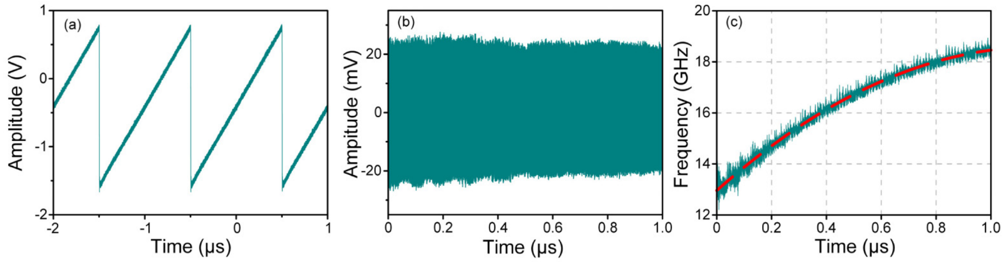

Fig. 3. (a) The measured control signal $S(t)$, (b) measured temporal waveform, (c) the recovered instantaneous frequency (the red dashed curve is the sine fitting curve).

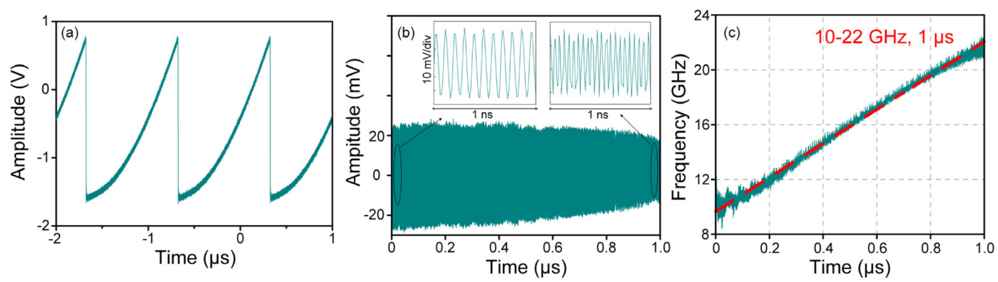

Fig. 4. (a) The measured control signal $S'(t)$, (b) measured LCMW (Insets: zoom-in views in temporal duration of 1ns), (c) the recovered instantaneous frequency (the red dashed curve is a linear fitting curve).

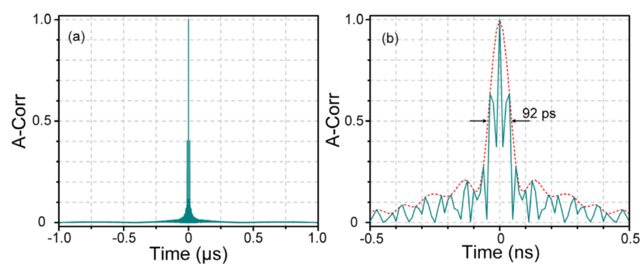

Fig. 5. (a) The calculated autocorrelation result, (b) zoom-in view of the autocorrelation peak (the red dashed curve is the fitted envelope).

Then, a 1-MHz control signal $S(t)$ which has a sawtooth profile and an amplitude of ~2.5 V is applied to the MZM, which is biased at the quadrature point. The waveform of the electrical control signal is shown in Fig. 3(a). At the output of the PD, a chirped microwave waveform with a temporal period of 1 μs is measured, as shown in Fig. 3(b). Figure 3(c) shows the recovered instantaneous frequency of the microwave waveform based on Hilbert transformation, where the dashed line is a sine fitting curve. As shown in Fig. 3(c), the instantaneous frequency covers a large bandwidth and increases from 12.9 GHz to 18.5 GHz. However, the instantaneous frequency increases nonlinearly, which is mainly due to the nonlinear injection amplitude control through the MZM, i.e., an MZM biased at the quadrature point has a nonlinear amplitude transfer function.

To get a linearly chirped microwave waveform, the control signal $S(t)$ has to be modified to compensate the frequency nonlinearity. In the above situation, as mentioned, the control signal $S(t)$ is a periodic sawtooth wave, and its one-period expression can be written as

$$S(t) = \frac{V_p t}{T}, 0 \le t \le T. \tag{1}$$

where V_p and T are the amplitude and temporal period of the sawtooth wave, respectively. The injection parameter ξ can be written as

$$\xi = \frac{E_{inj}(t)}{E_{SL}} = \frac{H[S(t)]}{E_{SL}}. \tag{2}$$

where $E_{inj}(t)$ and E_{SL} are the optical amplitude of injected light and free-running slave laser, respectively. H is the amplitude transfer function of MZM. Then the output microwave frequency f_o can be expressed as

$$f_o(t) = k\xi = k\frac{H[S(t)]}{E_{SL}} = k\frac{H\left[\frac{V_p t}{T}\right]}{E_{SL}}, 0 \le t \le T. \tag{3}$$

where k is a constant. By using a modified control signal $S'(t)$, the new output microwave frequency f_o' is assumed to linearly increase over time in a period, which can be written as

$$f_o'(t) = k\xi = k\frac{H[S'(t)]}{E_{SL}} = C \cdot t, 0 \le t \le T. \tag{4}$$

where C is a constant. From Eq. (3), we can calculate the expression of H using measured $f_o(t)$, i.e., the dashed curve in Fig. 3(c). Thus, the modified control signal $S'(t)$ can be obtained using Eq. (4) and its waveform is plotted in Fig. 4(a). With this method, the nonlinear microwave frequency modulation caused by the MZM and caused by the non-ideal constant coefficient k can be compensated. The generated LCMW is shown in Fig. 4(b), where the insets show the zoom-in views of the waveforms at the beginning and end of each period. Figure 4(c) shows the recovered instantaneous frequency of the LCMW. As can be seen, the LCMW is centered at 16 GHz with a bandwidth of 12 GHz (from 10 GHz to 22 GHz). The measured chirp rate is 12 GHz/μs. According to the result, the TBWP of the generated LCMW is $1.2\text{x}10^4$. It should be noted that, when the slave laser is operating at P1 dynamic state, the injection-shifted cavity resonance competes dynamically with the injection-imposed laser oscillation, thus not only the frequency difference but also the magnitude difference between two optical carriers varies with the injection parameter when the master-slave detuning frequency is fixed [20, 21]. Therefore, the amplitude of the generated LCMW fluctuates slightly as the frequency changes in the experiment. This problem can be solved by using either electrical or optical power limiting techniques. For instance, in [19], an optical limiting amplifier is used to compensate the amplitude variation.

To demonstrate the pulse compression capability, autocorrelation of the generated LCMW is calculated. The result is shown in Fig. 5(a), where a narrow peak is clearly observed. Through the zoom-in view of the autocorrelation peak in Fig. 5(b), the full width at half maximum (FWHM) is found to be 92 ps, indicating a pulse compression ratio of 10870 is achieved. Here, the generated LCMW is temporally continuous. To obtain pulsed microwave signals, an optical switch device can be applied before the PD, as demonstrated in [13].

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By changing the amplitude of the electrical control signal, the variation of optical injection parameter during one period is also changed and hence, bandwidth of the generated LCMW can be adjusted. As shown in Fig. 6, when the amplitude of the control signal is adjusted to ~1.6 V, bandwidth of the generated LCMW is changed to 5.5 GHz (central frequency: 16.25 GHz). The measured chirp rate is 5.5 GHz/μs and the TBWP is 5500. Besides, the central frequency of the LCMW can be tuned by simply changing the initial injection parameter using the optical attenuator. As shown in Fig. 7, by changing the injection parameter from ~0.9 to ~0.75, the central frequency of the generated LCMW is shifted from 16.25 GHz to 14.9 GHz with a bandwidth of 5.4 GHz (from 12.2 GHz to 17.6 GHz). The measured chirp rate is 5.4 GHz/μs, indicating a TBWP of 5400.

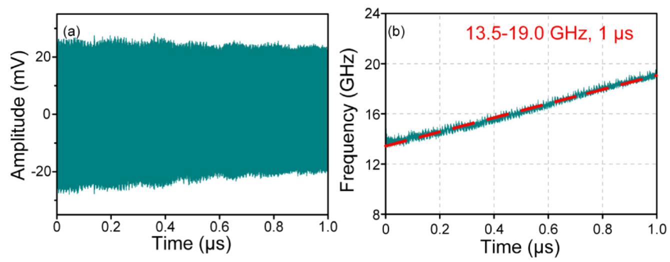

Fig. 6. (a) The measured LCMW, (b) the recovered instantaneous frequency (red dashed curve is the linear fitting curve).

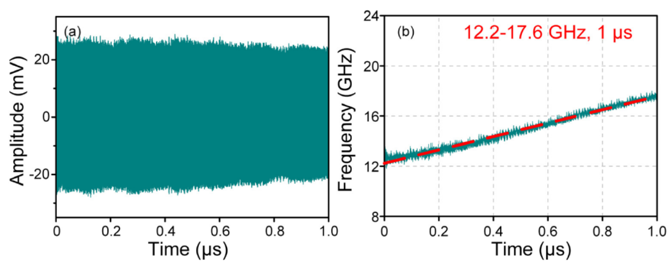

Fig. 7. (a) The measured LCMW, (b) the recovered instantaneous frequency (red dashed curve is the linear fitting curve).

By further properly configuring the control signal *S*(*t*), e.g., slowing down the tuning speed of *S*(*t*) to 100 kHz, an LCMW with a longer temporal duration of 10 μs is also generated, as shown in Fig. 8(a). Its instantaneous frequency is plotted in Fig. 9(b). As can be seen, the LCMW has an ultra large TBWP of about $1.2\text{x}10^5$ (10 μs, 12 GHz), which is significantly larger than most of the previously reported schemes.

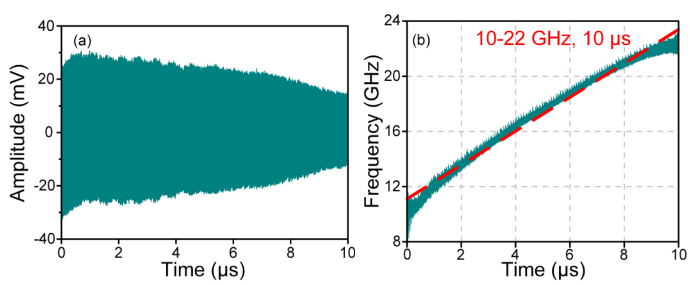

Fig. 8. (a) The measured LCMW, (b) the recovered instantaneous frequency (red dashed curve is the linear fitting curve).

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4. Discussion and conclusion

One thing that should be noticed is the polarization state of the injection light affects the injection efficiency and the resultant output frequency in the proposed system, which means the microwave frequency generated using the optically injected semiconductor laser is polarization-dependent. In the experiment, the output frequency f_0 can be tuned from 10.1 GHz to 22.2 GHz by simply tuning the polarization state of the injection light. As a result, LCMWs can also be achieved by replacing the intensity modulator in Fig. 1(a) with a polarization modulator (PolM) to manipulate the polarization state of the injection light, which increases the flexibility of the proposed LCMW generator. A further study on this topic is underway and it will be deeply discussed and demonstrated in the future work elsewhere.

In conclusion, we have proposed and demonstrated a novel and simple approach for photonic generation of LCMWs using an optically injected semiconductor laser. LCMW with ultra large TBWP can be generated by simply controlling the injection strength using a low-speed control signal. Compared with photonic schemes using spatial light modulator, fabricated FBG, femtosecond pulsed laser, high-speed EOM, high-speed electrical AWG or special designed wavelength sweeping laser, our approach only needs a commercial semiconductor laser and a low-speed intensity modulator. Since the intensity modulator in the system can be implemented using an integrated modulator, e.g., an electro-absorption modulator (EAM), the proposed LCMW generator can have a very compact structure. In the experiment, the generation of an LCMW with a TBWP as large as 1.2×10^5 (10 μs, 12 GHz) is demonstrated, which is significantly larger than most of the previously reported results. In addition, the feasibility of tuning the central frequency, temporal duration, bandwidth and corresponding TBWP of generated LCMW is also demonstrated. The proposed method features low cost, simple structure, large TBWP and high tunability, which may find wide applications in radar systems.

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