Multi-Band LFM Signal With Unidentical Bandwidths Subjected to Optical Injection in a DFB Laser

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***Abstract*— This letter demonstrates a tunable multi-band linear frequency modulation (LFM) signal with improved and unidentical bandwidths subjected to optical injection in a distributed-feedback (DFB) laser. In the proposed scheme, an optical beam is divided into two paths, one modulating with a baseband LFM signal and another with a power-varying signal. The basic principle of the proposed scheme is the optical beating of the carrier-suppressed ±1st sidebands in one path and the red-shifted emission mode of the DFB laser after optical injection in another path. In the experiment, the generated three LFM signals have the bandwidths of 11.5 GHz (from 23.0 to 34.5 GHz), 7.5 GHz (from 15.0 to 22.5 GHz), and 4 GHz (from 8.0 to 12.0 GHz) in one period of 1μ s. Moreover, we analyze the effect of the injected beam's frequency and power on the bandwidth tunability of the generated LFM signals.**

***Index Terms*— Multi-band LFM signal, optical injection, DFB laser.**

I. Introduction

LINEAR frequency modulation (LFM) signal is a typical and widely used pulse compression waveform in radar systems due to its ability to achieve an extensive detection range and a high range resolution [1]. Conventionally, LFM signals generated by the electrical methods have a limited frequency range, which restricts the radar system's performance. To overcome the drawbacks of the electrically generated LFM signals, several photonics-based approaches have been proposed to generate a single LFM signal with the improved frequency range and bandwidth [2]–[5]. Even though the range resolution is improved to the ultra-high range, a single-band radar system fails to fulfill the applications such as velocity detection and the Multiple Input Multiple Output (MIMO) radar system. Hence, a multi-band LFM signal with larger bandwidth, higher center frequency, and flexible tunability is of utmost importance for multi-functional modern radar systems [6].

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Several photonics approaches have been proposed for multi-band LFM signal generation. Among them, one approach is to use a single or dual-band LFM baseband signal to modulate an optical carrier by high-speed Mach-Zehnder modulator (MZM) for optical frequency multiplication, optical frequency comb and others [7]–[12] and then generate multi-band LFM signal. But this method suffers from a limited modulation index and needs a high-speed modulator. Fourier domain mode-locked optoelectronic oscillator has been proposed to generate a dual-band LFM signal, which suffers from limited bandwidth and poor linearity [13], [14]. Another approach is based on dual-beam injection to distributed-feedback (DFB) laser with Period-one (P1) oscillation state, where one of the injected beams is power-controlled by a near-saw tooth control signal [15]. But LFM signals generated from these approaches have either the same or opposite chirps, lacking flexibility and tunability. However, with the development of multi-function radar for different purposes, the generation of multi-band LFM signal with different bandwidths is required for detecting various targets, moving targets and other scenarios. Hence, multi-band LFM signal generation with unidentical and tunable bandwidths is an urgent task that needs to be solved.

This letter proposes a simple structure for multi-band LFM signal generation with unidentical and tunable bandwidths and high-frequency range. In the proposed scheme, an optical beam is divided into two paths. The optical beam in one path is modulated by a low-frequency electrical LFM signal for generating the carrier-suppressed ±1st sidebands. A saw-tooth waveform from an arbitrary wave generator (AWG) modulates the optical beam in another path, which functions as an intensity-controller of the injected beam. The injection of the intensity-controlled beam red-shifts the emission frequency of the DFB laser, a slave laser. Hence, the optical beating of the optical beams from two paths generates three LFM signals with unidentical bandwidths. The bandwidths of the generated LFM signals are given by the absolute value of sum and difference of the bandwidth of the modulating LFM signal and the red-shifted frequency range and double the bandwidth of the modulating LFM signal. In the experiment, three LFM signals with unidentical bandwidths of 11.5 GHz (from 23.0 to 34.5 GHz), 7.5 GHz (from 15.0 to 22.5 GHz), and 4 GHz (from 8.0 to 12.0 GHz) are generated. Also, the tunability analysis in bandwidth and center frequency of the generated LFM signals is demonstrated.

II. Experiment Set up and Operating Principle

The experiment setup of a multi-band LFM signal generation with unidentical bandwidths is shown in Fig. 1(a). The optical beam from a tunable laser (TL, Agilent N7714A) is divided into upper Path 1 and lower Path 2. In Path 1, the optical beam is modulated by an electric LFM signal through a Mach-Zehnder Modulator (MZM1, 10 Gb/s, Lucent 2623NA). Whereas in Path 2, the optical beam is modulated by an arbitrary waveform generator (AWG, 120 MHz, Agilent 85110A) through MZM2. Polarization controllers, PC1 and PC2, are used to control the polarization of optical beams. The output of MZM1 is directly sent to a photoelectric detector (PD) with a 3 dB bandwidth of 40 GHz via an optical coupler (OC), whereas the output of MZM2 is injected into a DFB laser (Actech LD15DM). The DFB laser's output after optical injection is sent to an optical filter to pass the emission mode of the DFB laser only. The filtered output is sent to the PD through an optical coupler, OC, where an optical beating with the optical beams from Path 1 occurs to generate the electrical LFM signals with unidentical bandwidths. The generated electric LFM signals are monitored in a real-time oscilloscope (Keysight, 32 GHz, DSO-X 92504A). An optical spectrum analyzer (OSA, Yokogawa AQ6370C) with a resolution of 0.02 nm is used to analyze the optical signals at different experiment setup stages.

The basic principle of the proposed multi-band LFM signal generation with unidentical bandwidths is the optical beating of $\pm 1^{st}$ sidebands of the modulated signal in Path 1 and the red-shifted emission mode of the DFB laser in Path 2, as illustrated in Fig. 1(b) and Fig. 1(c). Figure 1(b) shows the optical spectrum schematic at different stages of Fig. 1(a) as indicated by alphabets in red color (A-F). In Path 1, the optical signal from TL with a frequency of f_c is modulated by an LFM signal (f_{LFM}) with a bandwidth of B_{Mod}. As a result, two sidebands with the swept frequencies (f_{-1s} and f_{+1s}) are generated, as shown in Fig. 1(b-B). In this case, MZM1 is biased at minimum transmission bias (MITB) point; hence, optical carrier, f_c, is suppressed, and only f_{-1s} and f_{+1s} exist. The arrows in Fig. 1(b-B) are used to denote the sweeping of $\pm 1^{st}$ sidebands according to f_{LFM}. The optical beating of sweeping sidebands generates an LFM signal twice the bandwidth and center frequency of f_{LFM}.

In Path 2, the optical beam's power after the MZM2 varies according to the waveform of AWG. Then the power-varying optical beam, at point C of Fig. 1(a), is injected into a DFB laser. The frequency of the injected beam is chosen in such a way that it maintains a positive frequency detuning to the emission mode of the DFB laser and works in P_1 oscillation state [16]. As a result, the emission frequency (f_s) of the DFB laser decreases from f_{s0} to f_{s1}, shown in Fig.1(b-D), which is known as the red-shift of f_s. Hence, the frequency-range (B_{Inj}) of f_s can be controlled with the injected beam's power (power of f_c). Figure 1(b-E) illustrates the output beam after an optical filter, which passes only red-shifted f_s for an optical beating.

Next, the combined optical spectrums of Path 1 and Path 2 are shown in Fig. 1(b-F), passed through PD to generate LFM signals in the electric domain. The details

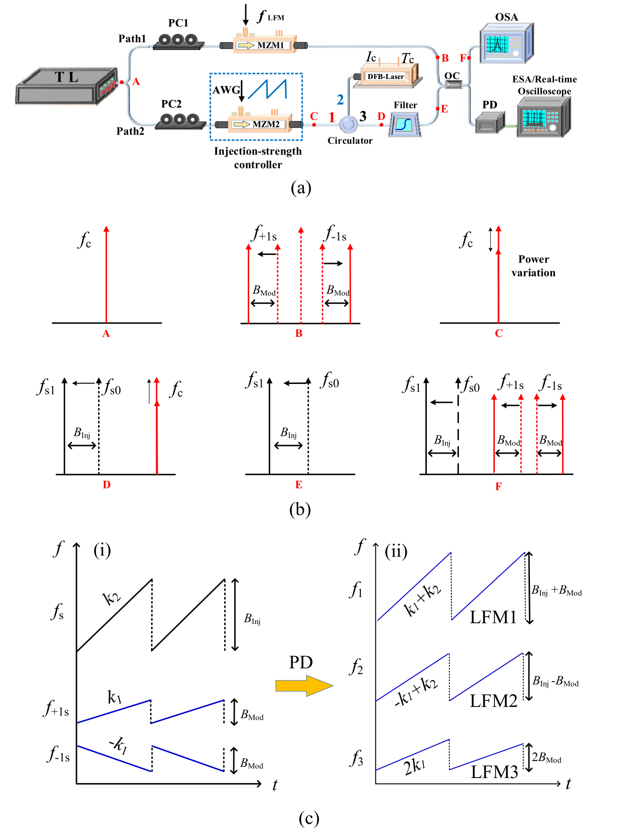

Fig. 1. Basic principle of multi-band LFM signal generation with unidentical bandwidths (a) block diagram, (b) optical spectrum schematic at different stages of block diagram indicated with red points in (a), and (c) the instantaneous frequency-time diagram before (i) and after (ii) PD.

of the electrical signals at the PD output are illustrated in Fig.1(c).

Figure 1(c-i) shows the instantaneous frequency-time diagram of that of Fig. 1(b-F), where we can see three linearly shifting frequencies with different chirps in one period. The chirp of f_s, f_{+1s}, and f_{-1s} are denoted by k_2, k_1, and $-k_1$, respectively. The optical beating of these signals in PD, three LFM signals, LFM1, LFM2, and LFM3, with different chirps, is generated, shown in Fig. 1(c-ii). LFM1 is generated by optical beating f_s and f_{-1s} ($f_1 = f_s - f_{-1s}$), which has a chirp of $k_1 + k_2$, LFM2 is generated by optical beating f_s and f_{+1s} ($f_2 = f_s - f_{+1s}$), which has a chirp of $-k_1 + k_2$, and LFM3 is generated by optical beating $f_{\pm 1s}$ ($f_3 = f_{+1s} - f_{-1s}$), which has a chirp of $2k_1$. The bandwidth of generated LFM signals is decided by B_{Mod} and B_{Inj}. The center frequency of the multi-band LFM signal can be tuned to a wide range by changing either the frequency of the tunable laser or the emission mode of the DFB laser.

III. Experiment Results

An optical beam with a wavelength of $f_c = 1553.25$ nm and optical power of 13.0 dBm (red dotted line in Fig. 2(a)) is divided into Path 1 and Path 2 using an OC with a coupling ratio of 50:50). In Path 1, f_c is modulated by f_{LFM} with the center frequency of 5 GHz, B_{Mod} of 2 GHz, and the period of 1.0 μs. The MZM1 is biased at MITB state with a biasing voltage of 3.814 V. As a result, f_c is suppressed, and the only $f_{\pm 1st}$ are observed, shown in the blue line of Fig. 2(a).

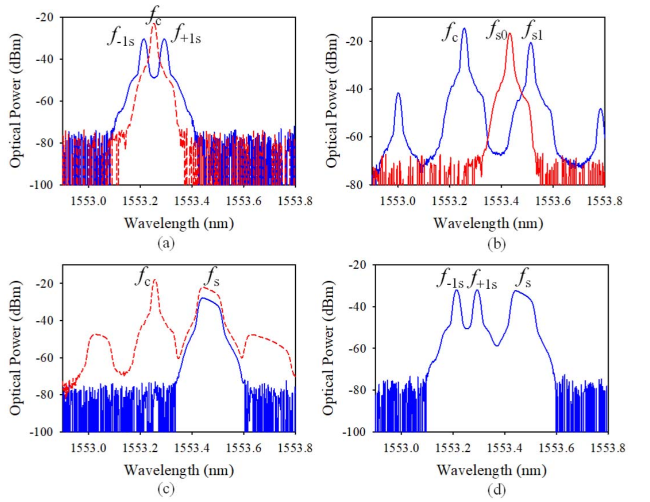

Fig. 2. Optical spectrum at different points of the experiment for multi-band LFM signal illustrated in Fig. 1(a). (a) dotted red line: Point A, solid blue line: Point B; (b) Point D without injection-strength controller; (c) dotted red line: Point D, solid blue line: Point E; and (d) Point F.

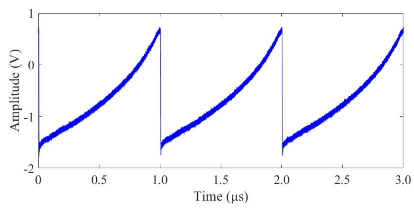

Fig. 3. The electric control signal S(t) with a near-saw tooth profile for the injection-strength controller.

In Path 2, f_c is injected into a DFB laser through an injection-strength controller. Figure 2(b) shows the optical spectrum of optical injection to the DFB laser with positive frequency detuning without the injection-strength controller. In Fig. 2(b), f_{s0} and f_{s1} are the free-running mode and the red-shifted mode after optical injection, respectively. The frequency detuning of f_c and f_{s1} is 32.33 GHz, and the red-shifted frequency range between f_{s0} and f_{s1} is 9.5 GHz. The small power spikes observed in Fig. 2(b) are unwanted harmonics signals generated due to the nonlinear dynamics of four-wave mixing in the laser cavity. In the proposed scheme, f_c is passed through the injection-strength controller, which is composed of 10-Gb/s MZM2 and an electrical control signal S(t) with a near-saw tooth profile generated by a 120-MHz AWG [5]. The electrical control signal, S(t), is shown in Fig. 3, which has a period of 1.0 μs and an amplitude of 3.5 V. The change in the power of the injected beam generates a red-shifted f_s with a bandwidth of B_{Inj}, which is shown by the red dotted line in Fig. 2(c). The solid blue line in Fig. 2(c) shows the optical spectrum after the optical filter, where unwanted harmonics and f_c are filtered out. Finally, optical signals from two paths are combined and measured by an OSA, as shown in Fig. 2(d). All three optical beams, f_{-1s}, f_{+1s} from Path 1, and red-shifted f_s from Path 2, observed in Fig. 2(d), are frequency-swept signals, and hence, the optical beating of these frequency-swept optical beams generates the multi-band LFM signal. The corresponding instantaneous frequency-time diagram of the blue line of Fig. 2(a) and the red line of Fig. 2(c) are shown in Fig. 4(a) and Fig. 4(b), respectively.

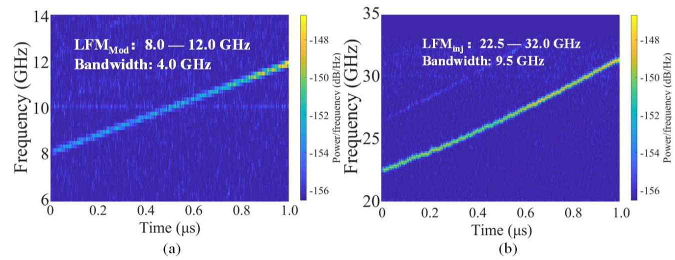

Fig. 4. The instantaneous frequency-time diagram of the LFM signal by beating the optical spectrum of (a): the blue line in Fig. 2(a), and (b): the red dotted line in Fig. 2(c).

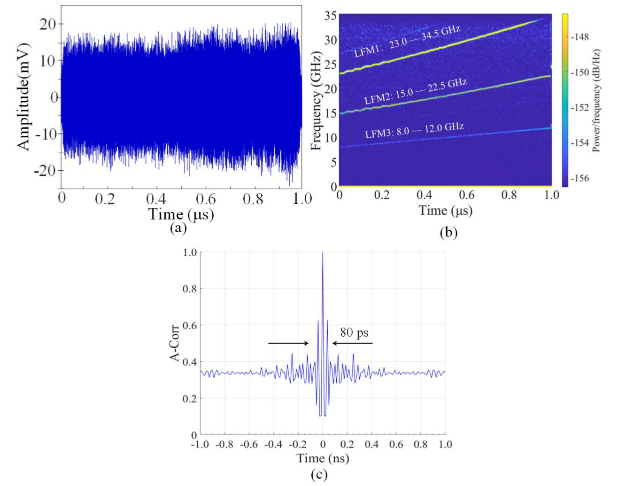

Fig. 5. The generated multi-band LFM signal of Fig. 2(d). (a) the temporal waveform, (b) the instantaneous frequency-time diagram, and (c) the autocorrelation function.

In Fig. 4(a), we see that an LFM signal (LFM$_{\text{Mod}}$) generated by the optical beating of $f_{\pm 1\text{st}}$ has limited bandwidth ($2B_{\text{Mod}}$) of 4 GHz (from 8.0 −12.0 GHz). Whereas in Fig. 4(b), we see that an LFM signal (LFM$_{\text{inj}}$) has a bandwidth (B_{Inj}) of 9.5 GHz (from 22.5-32.0 GHz), which is the red-shifted frequency range of the emission mode in the DFB laser, is much larger compared to that in Fig. 4(a). Even though the LFM generation by optical injection with a varying power provides higher bandwidth, the LFM signal generation is limited to a single LFM generation.

Figure 5(a) shows the temporal waveform of the generated multi-band LFM signal with a period of 1.0 μs, which is matched with the period of S(t) and f_{LFM}. Figure 5(b) shows the corresponding instantaneous frequency-time diagram. We observe that three LFM signals, LFM1, LFM2, and LFM3, are generated by optical heterodyning of f_s and f_{-1s}, f_s and f_{+1s}, and f_{-1s} and f_{+1s}, respectively. LFM1 has the bandwidth (B_1) of 11.5 GHz (from 23.0 to 34.5 GHz), equal to $B_{\text{Inj}}+B_{\text{Mod}}$. Similarly, LFM2 has a bandwidth (B_2) of 7.5 GHz (from 15.0 to 22.5 GHz), equal to $B_{\text{Inj}}-B_{\text{Mod}}$. Whereas LFM3 has a bandwidth (B_3) of 4 GHz (from 8.0 to 12.0 GHz), equal to $2B_{\text{Mod}}$. Figure 5(c) shows the autocorrelation function of the generated LFM signal, which has a full width at half maximum (FWHM) of about 80 ps, indicating a pulse compression ratio as high as 11500 [1].

To analyze the bandwidth's tunability of generated LFM signal, firstly, we keep f_{LFM} constant and decrease the injected beam's optical power from 13.0 dBm to 7.0 dBm

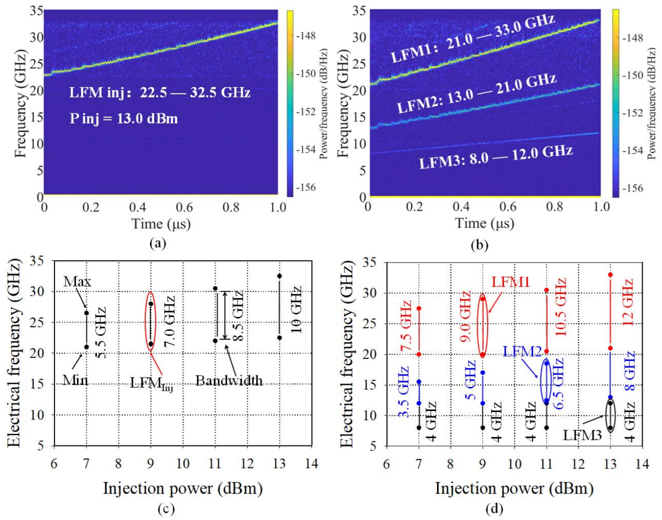

Fig. 6. (a) The generated $\mathrm{LFM_{Inj}}$ signal and (b) the multi-band LFM signal with the injected power of 13 dBm; (c) The generated $\mathrm{LFM_{Inj}}$ signal and (d) the generated three LFM signals at the output as the injected power is decreased.

with a step of 2 dB. For the comparison, we measure the bandwidth variation of the generated single LFM signals in Path 2 and after coupling Path 1 and Path 2, shown in Fig. 6. Figure 6 (a) and (b) show $\mathrm{LFM_{Inj}}$ and multi-LFM signals, respectively, when the injected power is 13.0 dBm. We observe that B_{Inj} is 10.0 GHz (from 22.5 to 32.5 GHz). As a result, the bandwidth of LFM1, LFM2, and LFM3 are separately recorded as 12.0 GHz (from 21.0 GHz to 33.0 GHz), 8 GHz (from 13.0 GHz to 21.0 GHz) and 4 GHz (from 8.0 to 12.0 GHz), which are equivalent to $B_{\mathrm{Inj}} + B_{\mathrm{Mod}}$, $B_{\mathrm{Inj}} - B_{\mathrm{Mod}}$, and $2B_{\mathrm{Mod}}$, respectively.

Next, as the optical power of the injected beam in Path 2 is decreased, the bandwidth variation of $\mathrm{LFM_{Inj}}$, and multi-LFM signal are shown in Fig. 6(c) and (d), respectively. In Fig. 6(c), "Max" and "Min" denote the maximum and minimum frequency values of the generated $\mathrm{LFM_{Inj}}$ signal, respectively. As the injected power is changed from 13.0 dBm to 7.0 dBm with a step of 2 dB, the bandwidth of $\mathrm{LFM_{Inj}}$ changes from 10.0 GHz (from 22.5 to 32.5 GHz) to 8.5 GHz (from 22.0 GHz to 30.5 GHz), 7.0 GHz (frequency from 21.0 to 28.0 GHz), and 5.5 GHz (from 21.0 to 26.5 GHz), respectively. In Fig. 6(d), the changes in bandwidths of LFM1(red), LFM2 (blue), and LFM3 (black) with a change in injected power are observed. When the injected beam power is changed from 13 dBm to 7 dBm in the interval of 2 dBm, the bandwidth of LFM1 is changed from 12.0 GHz (from 21.0 to 33.0 GHz) to 10.5 GHz (from 20.0 to 30.5 GHz), 9.0 GHz (frequency from 20.0 to 29.0 GHz), and 7.5 GHz (from 20.0 to 27.5 GHz), respectively. Similarly, the bandwidths of LFM2 is changed from 8 GHz (from 13.0 to 21.0 GHz) to 6.5 GHz (from 12.0 to 18.5 GHz), 5.0 GHz (frequency from 12.0 to 17.0 GHz), and 3.5 GHz (from 12.0 to 15.5 GHz), respectively. The bandwidth of LFM3 is constant as twice of that in f_{LFM}. Figure 6 confirms that the power variation of the injected beam in Path 2 changes the bandwidth of LFM1 and LFM2 according to the bandwidth combination of Path 1 and Path 2. Thus, the bandwidth of the generated LFM1 and LFM2 can be tuned easily by changing the injected beam's optical power in Path 2. It is also worth noting that the center frequency of the generated multi-LFM signal can be tuned easily by changing the wavelength of the injected beam or the center frequency of the modulated LFM signal in upper Path1.

IV. Conclusion

In conclusion, a multi-band LFM signal with unidentical and tunable bandwidths is proposed and demonstrated. The principle is the optical beating of carrier-suppressed $\pm 1^{\mathrm{st}}$ sidebands and the red-shifted emission mode of a DFB laser. In the experiment, the generated three LFM signals have the bandwidth of 11.5 GHz (from 23.0 GHz to 34.5 GHz), 7.5 GHz (from 15.0 GHz to 22.5 GHz), and 4 GHz (from 8.0 GHz to 12.0 GHz), respectively. Furthermore, the proposed scheme has the flexibility of tuning the bandwidth of LFM1 and LFM2 by controlling the injected beam's power. Hence, the proposed scheme of multi-band LFM signals with unidentical bandwidths has vast potential in the multi-function modern radar system.

References

[1] M. I. Skolnik, *Radar Handbook*, 3rd ed. New York, NY, USA: McGraw-Hill, 2008.

[2] J. Yao, "Photonic generation of microwave arbitrary waveforms," *Opt. Commun.*, vol. 284, no. 15, pp. 3723–3736, Jul. 2011.

[3] A. Kanno and T. Kawanishi, "Broadband frequency-modulated continuous-wave signal generation by optical modulation technique," *J. Lightw. Technol.*, vol. 32, no. 20, pp. 3566–3572, Oct. 15, 2014.

[4] Q. Guo, F. Zhang, P. Zhou, and S. Pan, "Dual-band LFM signal generation by optical frequency quadrupling and polarization multiplexing," *IEEE Photon. Technol. Lett.*, vol. 29, no. 16, pp. 1320–1323, Aug. 15, 2017.

[5] P. Zhou *et al.*, "Linearly chirped microwave waveform generation with large time-bandwidth product by optically injected semiconductor laser," *Opt. Exp.*, vol. 24, no. 16, pp. 18460–18467, Aug. 2016.

[6] J. Tian, J. Sun, G. Wang, Y. Wang, and W. Tan, "Multiband radar signal coherent fusion processing with IAA and apFFT," *IEEE Signal Process. Lett.*, vol. 20, no. 5, pp. 463–466, May 2013.

[7] D. Zhu and J. Yao, "Dual-chirp microwave waveform generation using a dual-parallel mach-zehnder modulator," *IEEE Photon. Technol. Lett.*, vol. 27, no. 13, pp. 1410–1413, Jul. 1, 2015.

[8] S. Zhu, M. Li, N. H. Zhu, and W. Li, "Transmission of dual-chirp microwave waveform over fiber with compensation of dispersion-induced power fading," *Opt. Lett.*, vol. 43, no. 11, pp. 2466–2469, Jun. 2018.

[9] Y. Xu, T. Jin, H. Chi, S. Zheng, X. Jin, and X. Zhang, "Photonic generation of dual-chirp waveforms with improved time-bandwidth product," *IEEE Photon. Technol. Lett.*, vol. 29, no. 15, pp. 1253–1256, Aug. 1, 2017.

[10] R. Cheng, W. Wei, W. L. Xie, and Y. Dong, "Photonic generation of programmable coherent linear frequency modulated signal and its application in X-band radar system," *Opt. Exp.* vol. 27, no. 26, pp. 37469–37480, 2019.

[11] P. Li *et al.*, "Photonic approach for the generation of switchable down-, up-, and dual-chirped linear frequency-modulated microwave signals," *Opt. Lett.*, vol. 45, no. 7, pp. 1990–1993, 2020.

[12] K. Zhang *et al.*, "Photonics-based multi-band linearly frequency modulated signal generation and anti-chromatic dispersion transmission," *Opt. Exp.*, vol. 28, no. 6, pp. 8350–8362, 2020.

[13] T. Hao, J. Tang, N. Shi, W. Li, N. Zhu, and M. Li, "Dual-chirp Fourier domain mode-locked optoelectronic oscillator," *Opt. Lett.*, vol. 44, no. 8, pp. 1912–1915, Apr. 2019.

[14] G. Y. Li *et al.*, "Photonic generation of dual-chirp microwave waveforms based on a tunable optoelectronic oscillator," *IEEE Photon. Technol. Lett.*, vol. 32, no. 10, pp. 559–602, May 15, 2020.

[15] H. Chen *et al.*, "Reconfigurable identical and complementary chirp dual-LFM signal generation subjected to dual-beam injection in a DFB Laser," *J. Lightw. Technol.*, vol. 38, no. 19, pp. 5500–5580, Oct. 8, 2020.

[16] S. C. Chan, S. K. Hwang, and J. M. Liu, "Period-one oscillation for photonic microwave transmission using an optically injected semiconductor laser," *Opt. Exp.*, vol. 15, no. 22, pp. 14921–14935, Oct. 2007.