



Photonics-based reconfigurable multi-band linearly frequency-modulated signal generation

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Abstract: A photonics-based multi-band linearly frequency-modulated (LFM) waveform generator with reconfigurable center frequency, bandwidth and time duration is proposed and demonstrated. By introducing two coherent optical frequency combs (OFCs) with a frequency shift and different free spectral ranges (FSRs) as multi-frequency optical LOs, a set of LFM signals with different center frequencies will be generated if one of the combs is modulated by an intermediate-frequency (IF) LFM signal. The center frequencies of the generated RF-LFM signals can be flexibly tuned by adjusting the frequency shift between the two OFCs. In addition, by introducing a series of proper time delays to the LFM signals and combining them, a frequency-stepped LFM signal can be generated. Furthermore, when the bandwidth of the IF-LFM signal equals the difference of the comb FSRs, and the time duration of IF-LFM signal equals the time delay of the consecutive channels, a LFM signal with both bandwidth and time duration multiplied can be obtained. With N comb lines, the maximum achievable time-bandwidth product (TBWP) is $N \times N$ times of the applied IF LFM signal. A proof-of-concept experiment is carried out. A set of LFM signals with frequencies ranging from L to Ka bands are generated. By introducing proper time delays, a frequency-stepped LFM signal with frequency steps between 10 GHz and 20 GHz is also produced. In addition, LFM signals with the bandwidth and time duration multiplied by 2 and 5 are realized (4-GHz bandwidth, 2- μ s time duration and 10-GHz bandwidth, 5- μ s time duration), respectively. Correspondingly, the TBWPs are increased by 4 and 25 times.

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1. Introduction

Modern radar systems are evolving to have multiple functions, demanding reconfigurable waveforms over multiple bands [1–3]. This requirement brings great challenges to electrical waveform generation [4,5]. In order to solve this problem, photonic technologies have been introduced to realize flexible waveform generation, especially the linearly frequency-modulated (LFM) signals, due to the advantages of broad instantaneous bandwidth and parallel processing capability brought by photonics [6–19]. One typical method to generate the LFM signal in the optical domain is to employ space-to-time mapping [6] or frequency-to-time mapping [7], which, however, can only produce RF signals with very small time duration (several nanoseconds). Another method is based on optical heterodyning of two linearly chirped optical pulses with different chirp rates [8–12]. These chirped optical pulses are usually generated by applying a quadratic phase to an optical pulse either through parabolic phase modulation [8,9] or dispersive elements [10–12]. But the time bandwidth products (TBWPs) of the generated waveforms are usually small (around 100). In [13], an electrically split parabolic signal for phase modulation is introduced to improve the TBWP, but the improvement is limited due to the deterioration of the generated signal's spectrum purity when increasing the slicing

of the parabolic phase modulation signal. To remedy this, the linearly chirped optical pulses can be generated by changing the electrical drive current of a semiconductor laser [14,15] or the power of an external injection light [16–18]. However, the bandwidth of the generated waveform is still restricted by the maximum achievable current or injection strength. The LFM signal can also be generated through frequency upconversion of an intermediate-frequency (IF) LFM signal in the optical domain [19]. All the mentioned methods above, however, are difficult to generate multiple reconfigurable LFM signals in different bands simultaneously.

Previously, only very few multi-band LFM signal generation approaches were proposed [20,21]. In [20], by using a polarization-division multiplexing dual-parallel Mach-Zehnder modulator (DPMZM), two frequency-quadrupling LFM signals in different bands are generated along two orthogonal polarization directions, respectively. However, only frequency quadrupling of the applied IF signal can be achieved, which limits the bandwidth, the center frequency and the reconfigurability of the generated signal. Furthermore, only two bands can be achieved since only two orthogonal polarization states can be applied. The approach in [21] generates multi-band LFM signals through frequency upconversion based on a mode-locked laser (MLL). A series of narrow-band optical filters are used to select the required optical spectral lines from the MLL, serving either as an optical carrier to be modulated by an electrical IF signal or the optical LOs to beat with the optically-carried IF signal. Frequency up-conversion of the IF signal to the desired RF bands can be implemented in a photodetector (PD). It should be mentioned that the generated waveforms are not limited to LFM signals in [21], thus this approach can be considered as “software defined”. However, in order to realize fine-tuning of the center frequency of the generated RF signals, the repetition rate of the MLL should be as small as possible (e.g., 400 MHz in [21]), which makes the selection of the required optical lines extremely challenge. In addition, the bandwidth and the time duration of the generated signals are equal to those of the applied IF signals, so the reconfigurability is limited.

In this paper, we propose and experimentally demonstrate a photonic approach for multi-band LFM waveform generation with reconfigurable bandwidth, center frequency and time duration. Two coherent optical frequency combs (OFCs) with different free spectral ranges (FSRs) are employed. Benefit from the multiple optical LOs provided by the OFCs, multi-band LFM signals can be generated simultaneously through frequency up-conversion of one low-frequency IF signal. The center frequencies of the generated multi-band signals can be easily tuned by adjusting the frequency shift between the two OFCs. In addition, by introducing proper time delays, these multi-band LFM signals can be combined to form a frequency-stepped LFM signal, and also can be combined to generate a LFM signal with both the bandwidth and time duration multiplied. A proof-of-concept experiment is carried out. Five sub-LFM signals with frequencies tuning from DC to 30 GHz are experimentally generated with 2-GHz bandwidth and 1- μ s time duration, and a frequency-stepped LFM signal with five frequency steps between 10 GHz and 20 GHz is also realized by carefully tuning of the time delays. In addition, a LFM signal with a bandwidth of 4 GHz and a time duration of 2 μ s centered at 14 GHz is achieved through stitching two time-delayed channels, so the TBWP is multiplied by 4. Moreover, the LFM signals centered at 5 GHz and 25 GHz, with the TBWP multiplied by 25 (i.e., 5×10^4 , 10-GHz bandwidth and 5- μ s time duration), are also realized by combining five time-delayed channels.

2. Principle

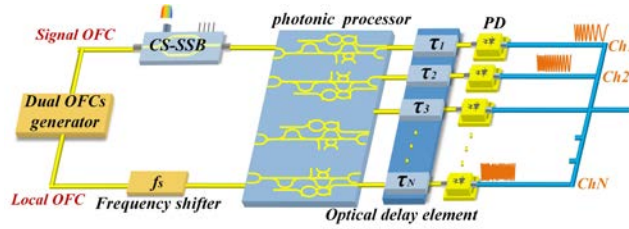


Fig. 1. Schematic diagram of the proposed reconfigurable multi-band LFM signal generator. OFC: optical frequency comb; CS-SSB: carrier-suppressed single sideband; PD: photodetector.

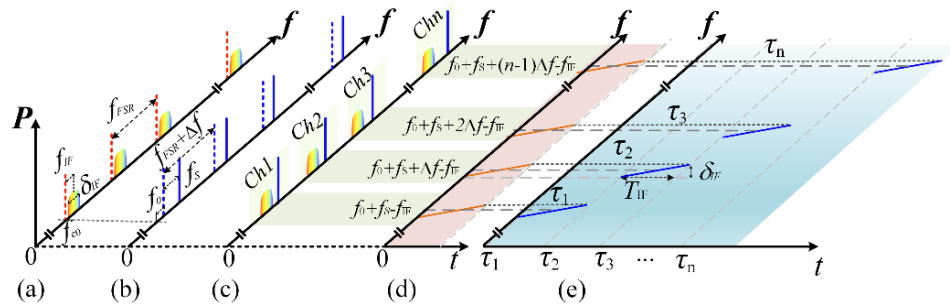


Fig. 2. Principle of the reconfigurable multi-band LFM signal generator. (a) The signal OFC before and after CS-SSB modulation; (b) the local OFC before and after frequency shifting; (c) the optical components selection by the photonic processor for different channels; (d) multi sub-LFM signals generation; (e) LFM/step-frequency LFM signals generation combined with multi time-delayed sub signals.

The schematic diagram of the proposed multi-band reconfigurable LFM signal generator with flexible center frequency, time duration and bandwidth based on two OFCs is shown in Fig. 1. The signal OFC and the local OFC with FSRs of f_{FSR} and $f_{\text{FSR}} + \Delta f$ are used, respectively, with the optical field expressions as follows

$$E_{\text{sig}}(t) \propto \sum_{n=1}^N e^{j2\pi t[f_{c0} + (n-1)f_{\text{FSR}}]} \quad (1)$$

$$E_{\text{lo}}(t) \propto \sum_{n=1}^N e^{j2\pi t[f_{c0} + f_0 + (n-1)(f_{\text{FSR}} + \Delta f)]}.$$

where f_{c0} , $f_{c0} + f_0$ denote the frequencies of the first comb line of the signal OFC and the local OFC, respectively, and N is the number of the comb lines. An IF-LFM signal centered at f_{IF} with a bandwidth of δ_{IF} and a time duration of T_{IF} is multicast by the signal OFC through carrier-suppressed single sideband (CS-SSB) modulation, as shown in Fig. 2(a). A frequency shift f_s is introduced to the local OFC, with the illustration of the optical spectra shown in Fig. 2(b). The frequencies of the n^{th} multicast copy of the modulated signal OFC and the n^{th} comb line of the frequency shifted local OFC can be written as

$$f_{\text{sig_modulation}}(n) = f_{c0} + (n-1)f_{\text{FSR}} + (f_{\text{IF}} + \delta_{\text{IF}}/2 - \delta_{\text{IF}}t/T_{\text{IF}}) \quad 0 \leq t \leq T_{\text{IF}} \quad (2)$$

$$f_{\text{lo_shifted}}(n) = f_{c0} + f_0 + (n-1)(f_{\text{FSR}} + \Delta f) + f_s.$$

For the n^{th} channel, the reconfigurable photonic processor is used to select the corresponding optical components in Eq. (2), as shown in Fig. 2(c). By introducing the optical signal of the n^{th} channel into a PD for square-law detection, the frequency of the output RF-LFM signal is as follows

$$f_{\text{out}}(n) = |f_0 + f_s + (n-1)\Delta f - (f_{\text{IF}} + \delta_{\text{IF}}/2 - \delta_{\text{IF}}t/T_{\text{IF}})| \quad 0 \leq t \leq T_{\text{IF}} \quad (3)$$

As can be seen, LFM signals centered at $f_0 + f_s + (n-1)\Delta f - f_{\text{IF}}$ ($n = 1, 2, \dots, N$) with the bandwidth of δ_{IF} and the time duration of T_{IF} are achieved, with the illustration shown in Fig. 2(d). The center frequencies of these LFM signals can be flexibly adjusted by tuning the frequency shift f_s . Furthermore, by introducing the time delays of $\tau_1, \tau_2, \tau_3, \dots, \tau_N$ ($\tau_{i+1} = \tau_i + \tau$) to the generated sub-band LFM signals, respectively, frequency-stepped LFM signals with a frequency step of Δf will be realized, as shown in Fig. 2(e). To avoid the time or spectrum aliasing, $T_{\text{IF}} \leq \tau$ and $\delta_{\text{IF}} \leq \Delta f$ should be satisfied. Especially, by adjusting τ to be equal to T_{IF} and Δf to be equal to δ_{IF} , LFM signals with both bandwidth and time duration multiplied will be obtained. In this way, multi-band LFM signals with reconfigurable bandwidth, time duration and center frequency would be generated.

3. Experimental demonstration

An experiment is carried out based on the schematic diagram shown in Fig. 1, and the experimental setup is shown in Fig. 3. The two OFCs are realized at an optical carrier of 1550.55 nm generated from a laser diode (LD, TeraXion NLL04), through two Mach-Zehnder modulators (MZMs, Fujitsu FTM7938EZ) in each branch. The frequency shifter is realized by another MZM (Fujitsu FTM7938EZ) modulated by an RF signal with the frequency of f_s and an optical filter (Yenista XTM-50). The 3-dB working bandwidth of the MZMs is 35 GHz. The electrical IF signal is generated by an arbitrary waveform generator (AWG, Keysight M8195A, 20 GHz), and modulated to the signal OFC through a DPMZM (EOSPACE Inc.) with CS-SSB modulation format. The 3-dB working bandwidth of the DPMZM is 35 GHz. The reconfigurable photonic processor is realized by a waveshaper (Finisar 16000s). The PDs (XPDV2120RA) have a bandwidth of 40 GHz and a responsivity of 0.65 A/W. The generated waveforms are observed by an 80-GSa/s real-time oscilloscope (Agilent DSO-X92504A), and the corresponding electrical spectra are measured by an electrical spectrum analyzer (ESA, R&S FSV40, 10 Hz-40 GHz). The optical spectra are observed by an optical spectrum analyzer with a resolution of 0.02 nm (Yokogawa AQ6370C).

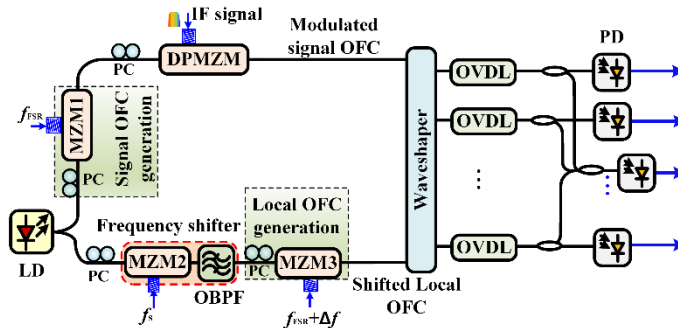


Fig. 3. Experimental setup of the proposed reconfigurable multi-band LFM signal generator. LD: laser diode; PC: polarization controller; MZM: Mach-Zehnder modulator; OBPF: optical bandpass filter; DPMZM: dual-parallel Mach-Zehnder modulator; OVDL: optical variable delay line.

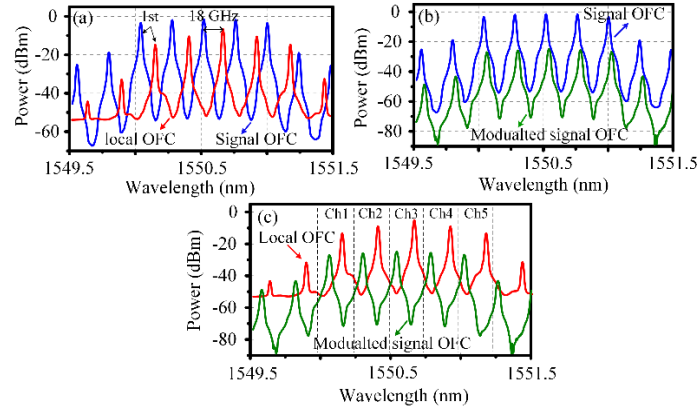


Fig. 4. Measured optical spectra of (a) signal OFC and local OFC with FSRs of 30 and 32 GHz respectively, (b) the signal OFC before and after modulation and (c) the selected optical components for the five channels by the photonic processor.

The FSRs of the signal OFC and the local OFC are set to be 30 and 32 GHz, respectively. It should be mentioned that in Fig. 3, the frequency shift f_s is firstly realized with the optical carrier, and then the local OFC is generated at the frequency shifted optical carrier. The function equals to the frequency shifted local OFC shown in Fig. 1. The frequency shift f_s is set to be 18 GHz. The optical spectra of the generated signal OFC and local OFC are shown in Fig. 4(a). As can be seen, the frequency difference between the 1st comb lines of the signal OFC and local OFC $f_s + f_0$ equals to 14 GHz. An IF-LFM signal centered at 3 GHz with a bandwidth of 2 GHz and a time duration of 1 μ s is modulated at the signal OFC through CS-SSB modulation format, with the optical spectrum shown in Fig. 4(b). Then the modulated signal OFC and the local OFC are injected to the photonic processor, selecting the required optical components corresponding to each channel, as shown in Fig. 4(c).

By injecting the selected optical components of each channel into a PD, reconfigurable frequency up-conversion will be achieved. Five sub-LFM signals with center frequencies of 11, 13, 15, 17 and 19 GHz are obtained simultaneously. The electrical spectra, the electrical waveforms and the time-frequency diagrams of the generated LFM signals are shown in Fig. 5.

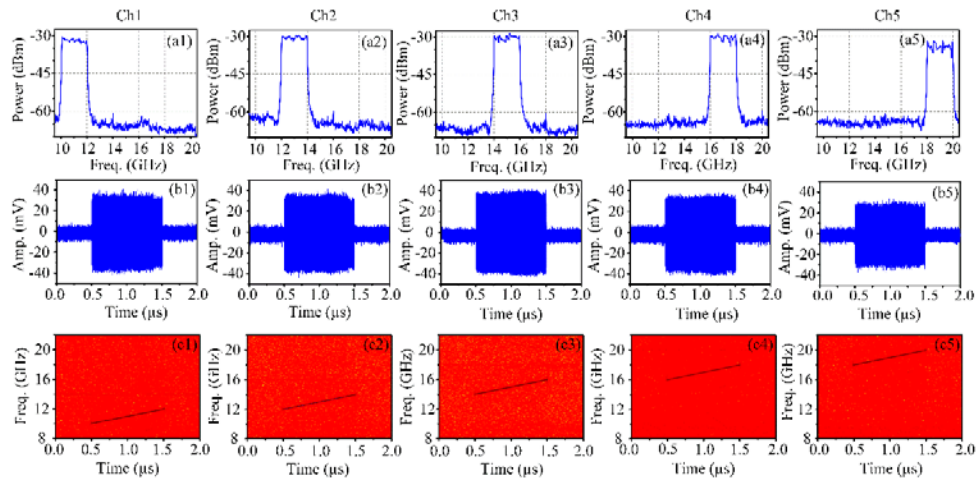


Fig. 5. The measured (a) electrical spectra, (b) waveforms and (c) time-frequency diagrams for the (1) 1st to (5) 5th channel, respectively.

By introducing proper time delays to the corresponding channels and combining the output signals, frequency-upconverted LFM signals with multiplied bandwidth and time duration will be obtained. In the experiment, an additional 1- μ s time delay (being equal to the time duration of the applied IF-LFM) is introduced to the 3rd channel by inserting a 200-m single mode fiber (SMF). By combining the optical output signals of the 2nd channel and the delayed 3rd channel together, an analog LFM signal centered at 14 GHz with 4-GHz bandwidth and 2- μ s time duration is successfully generated. The measured electrical spectrum, the waveform and the time-frequency diagram of the generated LFM signal are shown in Fig. 6(a)-6(c), respectively. The time duration and the bandwidth are both increased by two times. It should be mentioned that due to the experimental condition limitations, a 200-m SMF is inserted to realize the required time delay here. The feasibility of the proposed scheme can be guaranteed when an optical tunable time delay devices is used [22].

Frequency-stepped LFM signal is also realized. Time delays of 0, 2, 4, 6 and 8 μ s are added to the five sub-LFM signals in the digital domain, respectively. By combining these time delayed LFM signals together, frequency-stepped LFM signal with five frequency steps between 10 GHz and 20 GHz are generated. The normalized waveform and the corresponding time-frequency diagram are shown in Figs. 7(a) and 7(b), respectively.

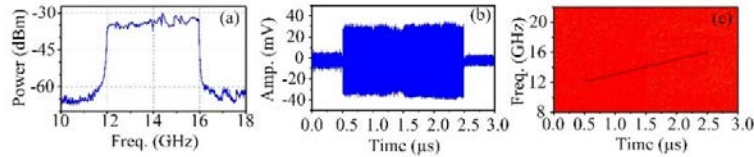


Fig. 6. The measured (a) electrical spectrum, (b) waveform and (c) the time-frequency diagram of the generated LFM signal centered at 14 GHz with 4-GHz bandwidth and 2- μ s time duration by combining the 2nd channel and the delayed 3rd channel.

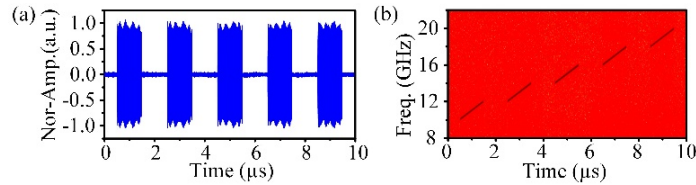


Fig. 7. (a) The normalized waveform and (b) the time-frequency diagram of the generated frequency-stepped LFM signal with five frequency steps between 10 GHz and 20 GHz by combining the five delayed sub-LFM signals in the digital domain.

The center frequencies of the generated LFM signals can be tuned by adjusting the shifting frequency f_s . When f_s is tuned to be 8 GHz, the center frequencies of the five generated sub-LFM signals are changed to be 1, 3, 5, 7 and 9 GHz, respectively. The OBPF has a minimum FWHM (full width at half maximum) of 6.25 GHz, so the out-band suppression of the frequency shifter can be guaranteed. The experimentally observed electrical spectra of these five LFM signals are shown in Fig. 8(a). The response of the OBPF will limit the working range of the frequency shifter, especially at low frequency. The limitation can be emitted by using other methods to realize the frequency shifter [23]. When f_s is set to be 28 GHz, another group of sub-LFM signals with the center frequencies of 21, 23, 25, 27 and 29 GHz is also realized, with the experimentally measured electrical spectra shown in Fig. 8(b). It can be seen that by adjusting the shifting frequency f_s , the generated LFM signals with frequencies tuning from L to Ka bands can be achieved.

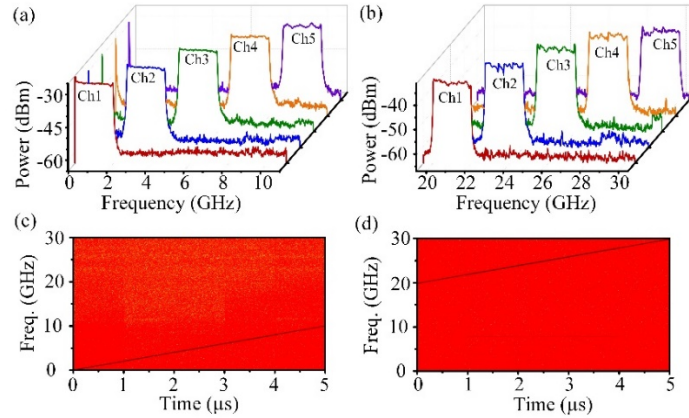


Fig. 8. The experimentally measured electrical spectra of the generated sub-LFM signals with frequencies tuning from DC to 30 GHz when f_s is set to be (a) 8 GHz and (b) 28 GHz. The time-frequency diagrams of the LFM signals with 10-GHz bandwidth and 5- μ s time duration by combining the time-delayed sub-LFM signals when f_s is set to be (c) 8 GHz and (d) 28 GHz.

By introducing time delays of 0, 1, 2, 3 and 4 μ s to the five sub-LFM signals shown in Figs. 8(a) and 8(b) in the digital domain, respectively, the LFM signals with 10-GHz bandwidth and 5- μ s time duration centered at 5 and 25 GHz are generated. The corresponding time-frequency diagrams are shown in Figs. 8(c) and 8(d), respectively. As can be seen, the time duration and the bandwidth are increased by five times and the corresponding TBWP as large as 5×10^4 can be achieved.

The bandwidth of the generated LFM signal can be also tuned by adjusting the bandwidth of the input IF signal. When the FSRs of the signal OFC and the local OFC are set to be 30 and 30.5 GHz, respectively, and f_s is set to be 27 GHz, Fig. 9(a) shows the optical spectra of the modulated signal OFC and the local OFC. By setting the IF-LFM signal to be one centered at 2 GHz with a 0.5-GHz bandwidth and a 1- μ s time duration, five sub-LFM signals with the bandwidth of 0.5 GHz and center frequencies of 24, 24.5, 25, 25.5 and 26 GHz are generated, respectively. By combining the five sub-LFMs with adding time delays of 0, 1, 2, 3 and 4 μ s, respectively, a LFM signal centered at 25 GHz with 2.5-GHz bandwidth and 5- μ s time duration is achieved. The corresponding electrical spectra and the time-frequency diagram are shown in Figs. 9(b) and 9(c), respectively.

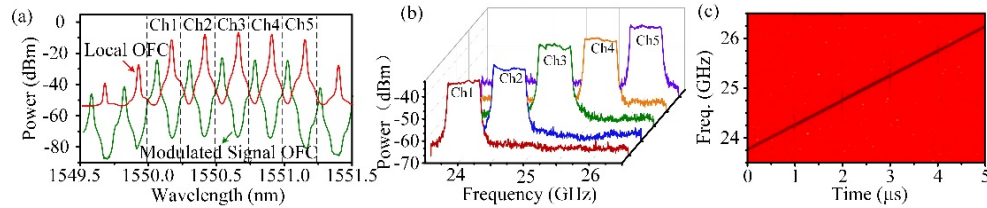


Fig. 9. (a) The optical spectra of the selected optical components into the photonic processor for the five channels when the 1.75-2.25 GHz IF-LFM signal is introduced, and (b) the corresponding electrical spectra of the experimentally output sub-band signals at each channel. (c) The time-frequency diagram of the generated LFM signal centered at 25 GHz with a bandwidth of 2.5 GHz and time duration of 5 μ s by combining the time-delayed sub-LFM signals.

It can be seen that by using the proposed scheme, multi-band LFM signals with reconfigurable bandwidth, time duration and center frequency can be realized. The maximum achievable TBWP is $N \times N$ times of the applied IF LFM signal (N is the comb line numbers). In addition, by introducing integrated microwave photonic technologies [22,24–26], the

proposed reconfigurable LFM signal generator can be realized in a chip, achieving better performance and compact size.

4. Conclusion

A photonics-based reconfigurable multi-band LFM signal generator with flexible center frequency, bandwidth and time duration is proposed and demonstrated. Multi-band LFM signals can be generated simultaneously by using only one low-frequency IF signal. The center frequencies of the generated multi-band signals can be easily tuned by adjusting the frequency shift between the two OFCs. By introducing proper time delays, these multi-band LFM signals can be combined to form a frequency-stepped LFM signal, and also can be combined to generate a LFM signal with both the bandwidth and the time duration multiplied. With N comb lines, the maximum achievable TBWP is $N \times N$ times of the applied IF LFM signal. LFM signals with frequencies tuning from L to Ka bands are experimentally generated. Frequency-stepped LFM signal with five frequency steps between 10 GHz and 20 GHz is also realized. Moreover, the LFM signals centered at 5 GHz and 25 GHz with 10-GHz bandwidth and 5- μ s time duration are generated, with the TBWP multiplied by 25 times to be as large as 5×10^4 . This approach can find applications in modern multi-functional multi-band radar systems.

Funding

Natural Science Foundation of Jiangsu Province (BK20160082); the Jiangsu Provincial Program for High-level Talents in Six Areas (DZXX-030); Fundamental Research Funds for Central Universities (NE2017002, NC2018005).

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