Optical Engineering

OpticalEngineering.SPIEDigitalLibrary.org

Thirteen coherent comb lines generated by a single integrated modulator

Dan Zhu
Zhiwen Chen
Wenjuan Chen
Shilong Pan

SPIE.

Dan Zhu, Zhiwen Chen, Wenjuan Chen, Shilong Pan, "Thirteen coherent comb lines generated by a single integrated modulator," *Opt. Eng.* **57**(2), 026116 (2018), doi: 10.1117/1.OE.57.2.026116.

Optical Engineering 57(2), 026116 (February 2018)

Thirteen coherent comb lines generated by a single integrated modulator

Dan Zhu, Zhiwen Chen, Wenjuan Chen, and Shilong Pan*
Nanjing University of Aeronautics and Astronautics, Key Laboratory of Radar Imaging and Microwave Photonics,
Ministry of Education, Nanjing, China

Abstract. A flexible flat optical frequency comb (OFC) generator based on a single integrated polarization-multiplexing dual-drive Mach–Zehnder modulator (PM-DMZM) and a single RF source is proposed and demonstrated. Only one PM-DMZM is required, which guarantees the simplicity. Due to the additional controllable parameter of the polarization as compared with conventional schemes, flat coherent OFCs can be obtained with relatively small modulation indices. A theoretical model is established and an experiment is carried out. Five-, 7-, 9-, 11- and 13-line OFCs with flatness of 0.5, 0.7, 1.2, 1.65, and 2.7 dB are experimentally demonstrated, respectively. [DOI: 10.1117/1.OE.57.2.026116]

Keywords: microwave photonics; optical frequency comb; polarization multiplexing.

Paper 171552 received Oct. 1, 2017; accepted for publication Jan. 12, 2018; published online Feb. 23, 2018.

1 Introduction

Optical frequency combs (OFCs) with high coherence among the comb lines are of great importance for a variety of microwave photonic applications.[1–4] Laser mode-locking,[5] fiber nonlinearities,[6–8] or external electro-optical modulation[9–15] is generally applied to generate the coherent OFCs, among which the methods using external electro-optical modulators (EOMs) feature high flexibility, low complexity, and high stability. Although cascaded EOMs can generate coherent OFCs with a relatively large number of comb lines,[9–10] the difficulty of controlling, insertion loss, system footprint, and cost will be dramatically increased with the number of modulators. In practice, however, an OFC with a comb line number around 10 is sufficient for many microwave photonic applications,[16–19] so schemes based on a single EOM become interesting due to its compact configuration.[11–15] But high modulation indices as well as a number of RF drive signals with strictly controlled frequencies or phases are always required, making the operation complicated. As an improvement, a 7-line OFC is obtained using only one RF source based on a single polarization modulator (PolM).[12] However, the optical signal needs to be divided into two independent paths, and an erbium-doped fiber amplifier is inserted in one path to flatten the comb lines, which inevitably degrades the comb lines' coherence. Another scheme to generate the flat OFC based on a single PolM applies a Brillouin-assisted power equalizer to achieve high flatness,[13] where separated optical paths are still needed. A standalone dual-parallel Mach–Zehnder modulator (DPMZM) can also produce flat OFCs with only one RF signal,[14] but the maximum achievable number of equal tones is 7. Based on a polarization-multiplexing dual-parallel Mach–Zehnder modulator (PM-DPMZM) that consists of six sub-MZMs, flat OFC can be generated.[15] However, large modulation indices are needed (for instance, a modulation index of 5.4 is required for 7-line OFC generation), and up to six DC bias voltages need to be controlled precisely, which would suffer severely from the well-known bias drift problem.

In this paper, we propose and demonstrate a flat coherent OFC generator based on a single integrated polarization-multiplexing dual-drive Mach–Zehnder modulator (PM-DMZM) and a polarizer, which is similar to a DPMZM but much simpler than a PM-DPMZM (i.e., the PM-DMZM has only two sub-MZMs and one third of that of a PM-DPMZM). As compared with the DPMZM, the PM-DMZM has one more controllable parameter (i.e., the polarization), which is utilized in the proposed OFC generator to increase the number of the generated comb lines and to lower the required modulation indices. A theoretical model is established and analyzed and an experiment is carried out. Five-, 7-, 9-, 11-, and 13-line OFCs with flatness of 0.5, 0.7, 1.2, 1.65, and 2.7 dB are experimentally generated, respectively.

2 Principle

Figure 1 shows the schematic diagram of the proposed OFC generator, which contains a laser diode (LD), a PM-DMZM, and a tunable polarizer. The LD generates a lightwave with an angular frequency of ω_c, which is sent to the PM-DMZM. The optical signal is split into two parts with equal powers in the PM-DMZM[20] and is modulated by an RF signal with a frequency of ω_m. In the upper branch, the modulated RF signal has an amplitude of V_{1m}, and the sub-DMZM (sub-DMZM1) is biased at $V_{\mathrm{bias}1}$. The optical field at the output of sub-DMZM1 can be written as

$$E_{\mathrm{out}1}(t) \propto E_0 e^{j\omega_c t}\left[e^{j\beta_1 \cos(\omega_m t)} + e^{j\beta_1 \cos(\omega_m t+\varphi_1)} e^{j\theta_1}\right], \tag{1}$$

where E_0 is the amplitude of the optical carrier, $\beta_1 = \pi V_{1m}/V_{\pi 1}$ is the modulation index, φ_1 is the phase difference between the two split RF signals in the upper branch, $\theta_1 = \pi V_{\mathrm{bias}1}/V_{\pi 1}$, and $V_{\pi 1}$ is the half-wave voltage of sub-DMZM1. Based on the Jacobi–Anger expansions, the optical field can be rewritten as

---

*Address all correspondence to: Shilong Pan, E-mail: pans@ieee.org

0091-3286/2018/$25.00 © 2018 SPIE

$$E_{\mathrm{out1}}(t) \propto E_0 e^{j\omega_c t}\left[\sum_{n=-\infty}^{\infty} j^n J_n(\beta_1) e^{jn\omega_m t}\cdot(1+e^{jn\varphi_1}\cdot e^{j\theta_1})\right], \tag{2}$$

where J_n is the n'th-order Bessel function of the first kind. Similarly, in the lower branch, the optical field output from sub-DMZM2 can be expressed as

$$E_{\mathrm{out2}}(t) \propto E_0 e^{j\omega_c t}\left[\sum_{n=-\infty}^{\infty} j^n J_n(\beta_2) e^{jn\omega_m t}\cdot(1+e^{jn\varphi_2}\cdot e^{j\theta_2})\right], \tag{3}$$

where $\beta_2 = \pi V_{2m}/V_{\pi 2}$ is the modulation index, V_{2m} is the amplitude of the modulated RF signal applied to sub-DMZM2, $\theta_2 = \pi V_{\mathrm{bias2}}/V_{\pi 2}$, φ_2 is the phase difference between the two split RF signals in the lower branch, and $V_{\pi 2}$ is the half-wave voltage of sub-DMZM2. The 90-deg polarization rotator in the lower branch makes the polarization states of the signals output from the two sub-DMZMs orthogonal. The two signals are combined and sent to a polarizer, of which the principal axis is tuned to have an angle of α with the principal axis of the PM-DMZM. Thus, the optical field at the output of the polarizer is given by

$$E_{\mathrm{out}}(t) \propto E_{\mathrm{out1}}(t)\cos\alpha + E_{\mathrm{out2}}(t)\sin\alpha\cdot e^{j\phi}, \tag{4}$$

where ϕ is the static phase difference between the two orthogonal polarization states, introduced by the polarizer. From Eq. (4), the optical power of the n'th-order sideband at the output of the polarizer can be written as

$$\begin{aligned}|E_{\mathrm{out}n}(t)|^2 \propto 4E_0^2\Bigg\{ & J_n^2(\beta_1)\cos^2\alpha\cdot\cos^2\left(\frac{n\varphi_1+\theta_1}{2}\right)\\ & + J_n^2(\beta_2)\sin^2\alpha\cdot\cos^2\left(\frac{n\varphi_2+\theta_2}{2}\right)\\ & + J_n(\beta_1)J_n(\beta_2)\sin 2\alpha\cdot\cos\left(\frac{n\varphi_1+\theta_1}{2}\right)\\ & \times\cos\left(\frac{n\varphi_2+\theta_2}{2}\right)\cos\left[\frac{n(\varphi_1-\varphi_2)+\theta_1-\theta_2}{2}-\phi\right]\Bigg\}.\end{aligned} \tag{5}$$

As can be seen from the aforementioned equation, the relative amplitude of the sidebands can be adjusted to have the same power by tuning β_1, β_2, φ_1, φ_2, θ_1, θ_2, ϕ, and α. A flat OFC can be realized in this way. For the 5-, 7-, 9-, 11-, and 13-line OFC generations, typical power variation contour plot calculated according to Eq. (5) is shown in Figs. 2(a)–2(e), respectively. The corresponding used values of φ_1, φ_2, θ_1 (represented by V_{bias1}), θ_2 (represented by V_{bias2}), ϕ, and α are shown in Table 1. With β_1 and β_2 being set to satisfy the optimum regions marked as "A," i.e., around "1.7 and 1.8," "1.5 and 2.2," and "3.2 and 3.1," for the 5-, 7-, and 9-line OFC generations, respectively, the flatness of the generated OFC is within 1 dB. For the generation of 11- and 13-line OFCs with flatness of better than 2 dB, the requirements of the modulation indices β_1 and β_2 are around "4.5 and 5.5" and "5 and 5.7," respectively, satisfying the optimum regions marked as "B." As such, based on the integrated polarization-multiplexing structure of the PM-DMZM, flat OFCs can be generated with relatively low modulation indices. Since the comb lines are generated from the same optical carrier and no physical path separation is introduced to the scheme, there would be good coherence among the comb lines.

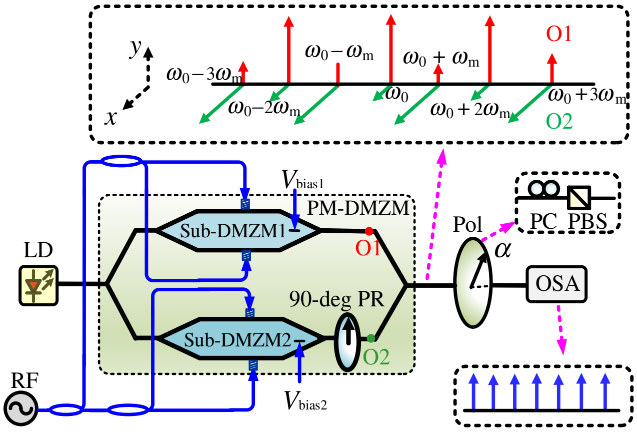

Fig. 1 Schematic diagram of the proposed coherent OFC generator based on a PM-DMZM and a polarizer. LD, laser diode; DMZM, dual-drive Mach–Zehnder modulator; PM-DMZM, polarization-multiplexing dual-drive Mach–Zehnder modulator; PR, polarization rotator; Pol, polarizer; PC, polarization controller; PBS, polarization beam splitter; and OSA, optical spectrum analyzer.

For the 7-line OFC generation, a group of typical simulation parameters are selected, i.e., $V_{\mathrm{bias1}} = 0$ V, $V_{\mathrm{bias2}} = 7$ V, $\beta_1 = 1.5$, $\beta_2 = 2.3$, $\alpha = 5.13$, $\varphi_1 = 0.89$, $\varphi_2 = 1.85$, and $\phi = 0.01$. The simulated output orthogonal optical signals in the two branches and the obtained 7-line OFC with a flatness of 0.6 dB are shown in Figs. 3(a)–3(c), respectively. The simulation for the generation of 13-line OFC is shown in Fig. 4. As can be seen, when the parameters are set to be $V_{\mathrm{bias1}} = 0$ V, $V_{\mathrm{bias2}} = 7$ V, $\beta_1 = 5$, $\beta_2 = 5.7$, $\alpha = 5.29$, $\varphi_1 = 4.97$, $\varphi_2 = 0.01$, and $\phi = 0.01$, a 13-line OFC with a flatness of 2 dB is generated. The simulated output orthogonal optical signals in the two branches and the final obtained 13-line OFC with a flatness of 2 dB are shown in Figs. 4(a)–4(c), respectively. As can be seen from Figs. 3 and 4, due to the introduction of the additional controllable parameter of the polarization, there is no need to make each output optical components of sub-DMZM1 or sub-DMZM2 have the same amplitude, so high modulation indices are not required.

For OFC generation with 5-13 comb lines, the simulated typical parameters are shown in Table 1. It can be seen that OFCs can be generated with relatively low modulation indices due to the additional controllable parameter of polarization using the proposed scheme.

3 Experimental Results and Discussions

An experiment based on the scheme shown in Fig. 1 is carried out. The CW light from the LD (TeraXion NLL04) has a wavelength of 1550.548 nm. The PM-DMZM (Fujitsu FTM7980EDA) has a working bandwidth of 20 GHz and a half-wave voltage of 3.5 V. The modulated RF signal is generated by a microwave signal generator (Keysight N5183B). The tunable polarizer is realized by connecting a polarization controller (PC) to a polarization beam splitter (PBS). An optical spectrum analyzer (OSA, Yokogawa

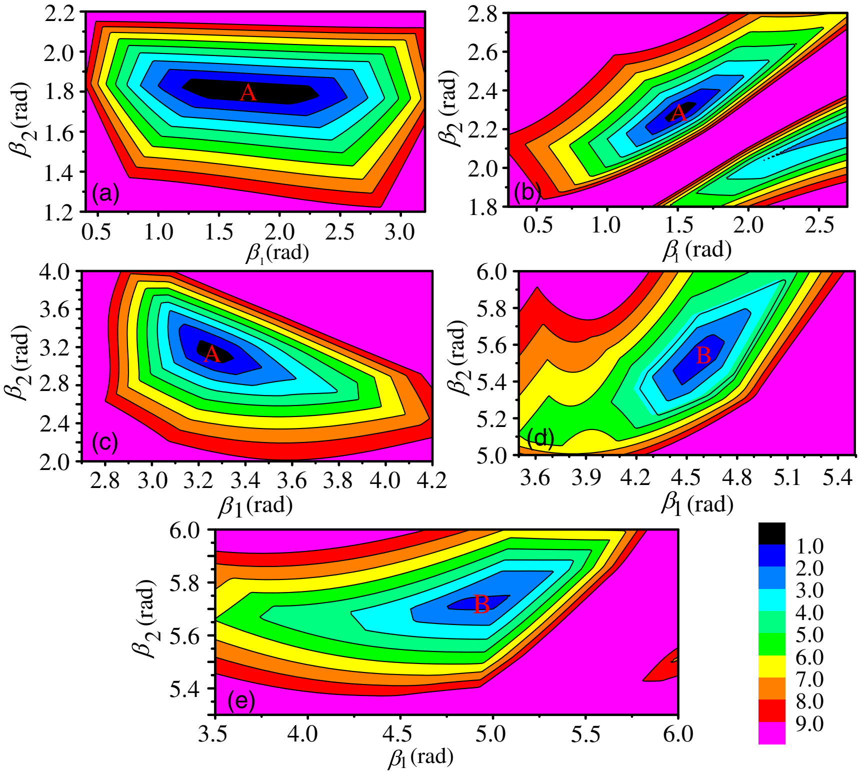

Fig. 2 Typical power variation contour plot versus β_1 and β_2 calculated for (a) 5-, (b) 7-, (c) 9-, (d) 11-, and (e) 13-line OFC generations.

Table 1 Simulated typical parameters for OFC generation with different comb line numbers.

Comb numbers	V_{bias1} (V)	V_{bias2} (V)	α (rad)	φ_1 (rad)	φ_2 (rad)	ϕ (rad)	β_1	β_2	Flatness (dB)
5	3.5	0	4.17	2.73	3.13	0.01	1.8	1.8	0.06
7	0	7	5.13	0.89	1.85	0.01	1.5	2.3	0.6
9	0.8	2.4	5.61	4.81	4.01	4.81	3.3	3.1	0.72
11	0	7	5.37	5.77	2.25	0.01	4.5	5.5	1.46
13	0	7	5.29	4.97	0.01	0.01	5	5.7	2

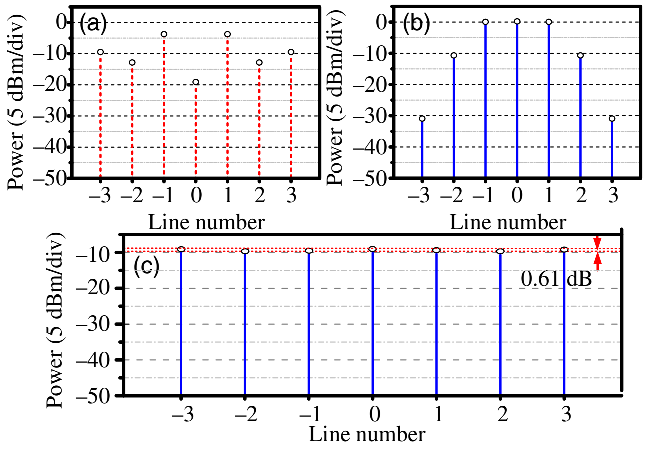

Fig. 3 The simulated output spectra of (a) sub-DMZM1 and (b) sub-DMZM2, and (c) the generated 7-line OFC.

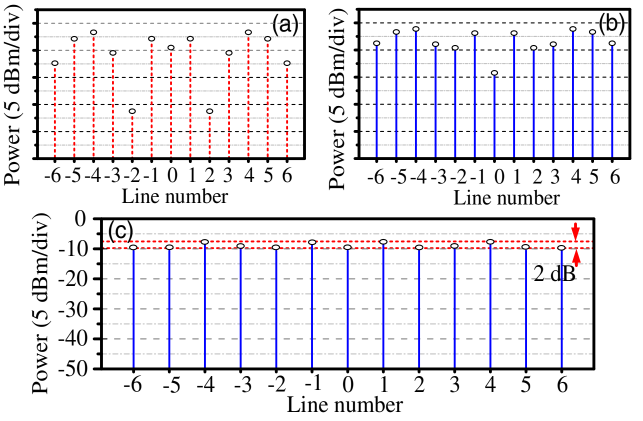

Fig. 4 The simulated output spectra of (a) sub-DMZM1 and (b) sub-DMZM2, and (c) the obtained 13-line OFC.

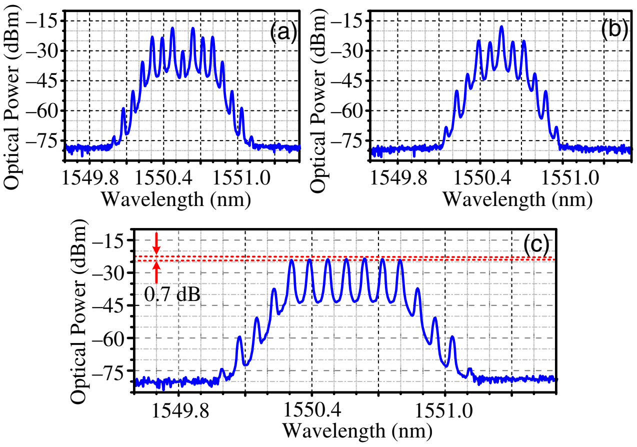

Fig. 5 Experimental optical spectra of (a), (b) the two orthogonally polarized signals split by a PBS connected to the PC following the PM-DMZM for the 7-line OFC generation, and (c) the generated 7-line OFC.

AQ6370C) with a resolution of 0.02 nm is used to observe the optical spectra.

To generate a 7-line OFC, the bias voltages are set to be $V_{\text{bias1}} = 4.37$ V, $V_{\text{bias2}} = 5.32$ V, and the powers of the driven 10-GHz RF signal in the upper and lower branches are set to be 18.6 and 21.65 dBm, respectively. The corresponding modulation indices are 1.71 and 2.43, respectively. The optical spectra of the two orthogonally polarized signals at the outputs of sub-DMZM1 and sub-DMZM2 are shown in Figs. 5(a) and 5(b), respectively. By tuning the PC following the PM-DMZM to make the principle axis of the polarizer to have a proper angle with the principal axis of the PM-DMZM, a flat 7-line OFC is successfully generated with a flatness of 0.7 dB, as shown in Fig. 5(c). The experimental results agree well with the theoretically simulated results for 7-line OFC generation.

Figure 6 shows the experimental results for the 5-, 9-, 11-, and 13-line OFC generations, respectively, including the two orthogonally polarized signals at the outputs of sub-DMZM1 and sub-DMZM2, and the obtained flat OFCs. For the 9-line OFC generation, the RF power is set to be 23.84 and 24.58 dBm, respectively, corresponding to modulation indices of 3.13 and 3.4. The flatness of the OFC is 1.2 dB. By setting the RF power in the upper and lower branches to be 27.5 and 29 dBm, respectively, a flat 11-line OFC is generated with a flatness of 1.65 dB, while the corresponding modulation indices are only 4.8 and 5.7. A flat 13-line OFC with a flatness of 2.7 dB is also generated by setting the RF power in the upper and lower branches to be 28.4 and 29.4 dBm, corresponding to modulation indices of 5.3 and 5.9, respectively.

Using the proposed scheme, a flat OFC generator is realized with no need of high modulation indices, using only one single modulator and one single RF source. In the proposed work, using electrical controlled PCs and feedback controlling circuits, the parameters of φ_1, φ_2, ϕ, and α can be controlled and adjusted precisely to further improve the system performance. And the stability and performance of the system can also be further improved using a DC bias controlling circuit to control the parameters of θ_1 and θ_2. In addition, the static phase difference ϕ between the two polarizations introduced by the polarizer is theoretically simulated as a variable since the polarizer is formed by combining a PC and a PBS. It can be set to have a certain value to make the operation simpler.

4 Conclusion

In conclusion, a method to generate flat coherent OFCs using only a PM-DMZM and a single-frequency RF source has

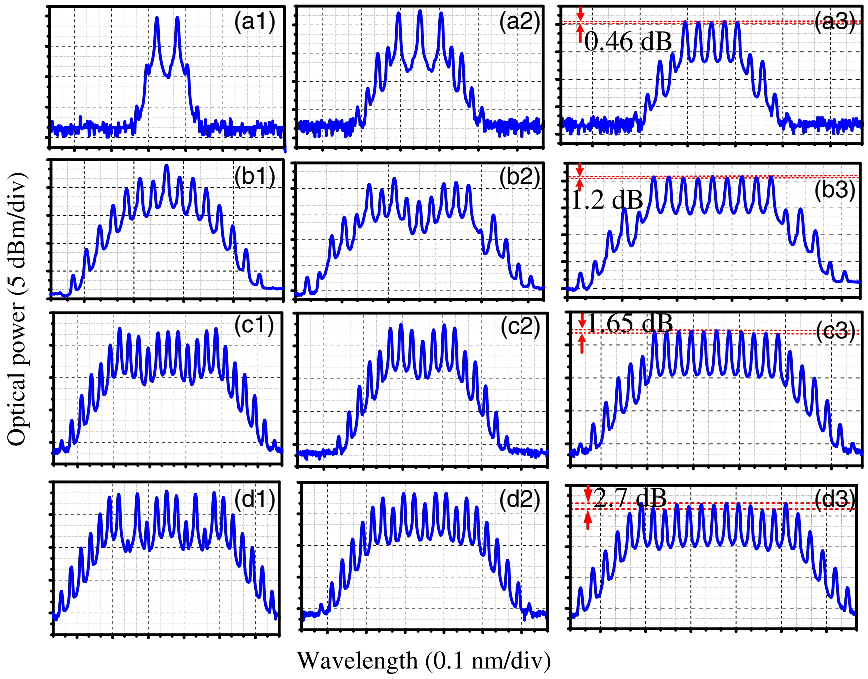

Fig. 6 Experimental optical spectra of the two orthogonally polarized signals split by a PBS connected to the PC following the PM-DMZM and the final obtained OFCs for (a1), (a2), and (a3) the 5-line generation; (b1), (b2), and (b3) the 9-line generation; (c1), (c2), and (c3) the 11-line generations; and (d1), (d2), and (d3) the 13-line generation.

been proposed and demonstrated. Flat OFCs with up to 13 lines have been generated experimentally. The simplicity is guaranteed, and flat OFCs can be obtained flexibly with relatively small modulation indices due to the additional controllable parameter of polarization. The proposed scheme can find applications in microwave photonic signal generation and processing applications.

Acknowledgments

This work was supported by the Fundamental Research Funds for the Central Universities (No. NS2016037).

References

1. P. Ghelfi et al., "A fully photonics-based coherent radar system," *Nature* **507**(7492), 341–345 (2014).
2. S. L. Pan et al., "Satellite payloads pay off," *IEEE Microwave Mag.* **16**(8), 61–73 (2015).
3. I. Coddington, N. Newbury, and W. Swann, "Dual-comb spectroscopy," *Optica* **3**(4), 414–426 (2016).
4. H.-J. Kim, D. E. Leaird, and A. M. Weiner, "Rapidly tunable dual-comb RF photonic filter for ultra broadband RF spread spectrum applications," *IEEE Trans. Microwave Theory Tech.* **64**(10), 3351–3362 (2016).
5. D. Zhu et al., "A coupled optoelectronic oscillator based on enhanced spatial hole burning effect," in *IEEE Int. Topical Meeting on Microwave Photonics (MWP '16)*, pp. 177–180 (2016).
6. J. L. S. Brito, P. C. Dainese, and F. C. Cruz, "Optical frequency comb based on single-pass four-wave-mixing in a HNLF combined with EO-modulation," in *CLEO: Science and Innovations*, Optical Society of America (2016).
7. T. Yang et al., "Comparison analysis of optical frequency comb generation with nonlinear effects in highly nonlinear fibers," *Opt. Express* **21**(7), 8508–8520 (2013).
8. V. R. Supradeepa and A. M. Weiner, "Bandwidth scaling and spectral flatness enhancement of optical frequency combs from phase-modulated continuous-wave lasers using cascaded four-wave mixing," *Opt. Lett.* **37**(15), 3066–3068 (2012).
9. C. He et al., "Ultraflat optical frequency comb generated based on cascaded polarization modulators," *Opt. Lett.* **37**(18), 3834–3836 (2012).
10. R. Wu et al., "Generation of very flat optical frequency combs from continuous-wave lasers using cascaded intensity and phase modulators driven by tailored radio frequency waveforms," *Opt. Lett.* **35**(19), 3234–3236 (2010).
11. A. K. Mishra et al., "Flexible RF-based comb generator," *IEEE Photonics Technol. Lett.* **25**(7), 701–704 (2013).
12. C. Chen, F. Zhang, and S. Pan, "Generation of 7-line optical frequency comb based on a single PolM," *IEEE Photonics Technol. Lett.* **25**(22), 2164–2166 (2013).
13. W. Li et al., "Generation of flat optical frequency comb using a single polarization modulator and a Brillouin-assisted power equalizer," *IEEE Photonics J.* **6**(2), 1–8 (2014).
14. Q. Wang et al., "Ultra-flat optical frequency comb generator using a single-driven dual-parallel Mach–Zehnder modulator," *Opt. Lett.* **39**(10), 3050–3053 (2014).
15. T. Lin et al., "Generation of flat optical frequency comb based on a DP-QPSK modulator," *IEEE Photonics Technol. Lett.* **29**(1), 146–149 (2017).
16. S. L. Pan and J. P. Yao, "Photonics-based broadband microwave measurement," *J. Lightwave Technol.* **35**(16), 3498–3513 (2017).
17. K. Xu et al., "Microwave photonics: radio-over-fiber links, systems, and applications," *Photonics Res.* **2**(4), B54–B63 (2014).
18. W. Y. Xu, D. Zhu, and S. L. Pan, "Coherent photonic RF channelization based on dual coherent optical frequency combs and stimulated Brillouin scattering," *Opt. Eng.* **55**(4), 046106 (2016).
19. M. Xue et al., "Wideband optical vector network analyzer based on optical single-sideband modulation and optical frequency comb," *Opt. Lett.* **38**(22), 4900–4902 (2013).
20. W. J. Chen et al., "Full-duty triangular pulse generation based on a polarization multiplexing dual-drive Mach–Zehnder modulator," *Opt. Express* **24**(25), 28606–28612 (2016).

Dan Zhu received her BS and PhD degrees in electronics engineering from Tsinghua University, Beijing, China, in 2004 and 2009, respectively. In May 2011, she joined the Key Laboratory of Radar Imaging and Microwave Photonics (Nanjing Univ. Aeronaut. Astronaut.), Ministry of Education, China, where she is now an associate professor. Her current research interests include microwave photonic signal generation and processing.

Shilong Pan received his BS and PhD degrees in electronics engineering from Tsinghua University, Beijing, China, in 2004 and 2008, respectively. From 2008 to 2010, he was a "Vision 2010" Postdoctoral Research fellow in the Microwave Photonics Research Laboratory, University of Ottawa, Canada. Currently, he is a full professor and executive director at the Key Laboratory of Radar Imaging and Microwave Photonics (Nanjing Univ. Aeronaut. Astronaut.), Ministry of Education, China.

Biographies for the other authors are not available.