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A two-stage optical frequency comb generator based on polarization modulators and a Mach–Zehnder interferometer

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ABSTRACT

A two-stage optical frequency comb (OFC) generator is proposed based on two polarization modulators (PolMs) and a Mach–Zehnder interferometer (MZI). In the first-stage OFC generator, a group of even-order sidebands and a group of odd-order sidebands are generated with similar powers, respectively, based on a single PolM. By tuning the power difference between the two sideband groups using an MZI, a flat OFC with increased comb-lines can be generated. In the experiment, OFCs with up to 11 comb-lines are generated with good flatness, which is better than most of the previous scheme based on a single modulator. To further increase the comb-line number, a second-stage OFC generator is followed using another PolM, which could increase the comb-line number by a factor of up to 5 theoretically. Performance of the proposed two-stage OFC generator is investigated through simulations and experiments. The results can verify the feasibility of the proposed OFC generator, which is a cost-effective way to generate flat OFCs with a large number of comb-lines.

1. Introduction

Optical frequency comb (OFC) has applications in many fields such as optical arbitrary waveform generation, microwave photonic signal processing, precise optical metrology, and dense wavelength division multiplexed transmission systems [1–4]. Many schemes have been demonstrated for OFC generation. For example, an OFC can be generated by a mode-locked laser [5], which needs a complicated feedback loop to achieve stable operation and the comb line spacing is hard to be tuned. Fiber nonlinearities, such as the stimulated Brillouin scattering (SBS) and four-wave mixing (FWM) effects can also be utilized for OFC generation [6,7], but these methods need high power optical amplifiers and complicated structures. Another effective way to generate an OFC is to modulate a continuous wave (CW) light source using an electro-optic modulator (EOM), which features stable operation, high flexibility and easily tunable comb spacing. When a multi-stage OFC generator consisting of multiple cascaded modulators is applied, the number of comb-lines can be increased. Usually, the more comb-lines are generated by a single modulator, the more comb-lines can be obtained for the multi-stage OFC generator. However, the number of comb-lines or the power flatness of the OFC generated by a single modulator is usually limited. In Ref. [8], a dual-parallel Mach–Zehnder modulator (DPMZM) is used to generate a seven-line OFC, where the three bias voltages of the DPMZM should be carefully controlled to achieve good power flatness. When a single polarization modulator (PolM) or a Mach–Zehnder modulator (MZM) is applied, a very flat OFC with five comb lines can be obtained [9,10]. Also using a PolM, if the power difference between the even-order sidebands and the odd-order sidebands was adjusted by an optical amplifier, a seven-line OFC with good flatness was generated [11]. Again, the use of optical amplifier increases the complexity and power consumption. By strong sinusoidal phase modulation of a CW light, an OFC with many comb-lines can be generated, but the power flatness is poor. To get a better flatness, gating the input CW light into short optical pulses is an effective solution, which can be realized using additional intensity modulators [12]. To further increase the power flatness, the radio frequency signal that drives the phase modulator can be properly tailored, as demonstrated in Ref. [13], where 38 comb-liens with 1 dB power flatness is achieved using two intensity modulators and one phase modulator.

In this paper, we propose and experimentally demonstrate a two-stage OFC generator. The first-stage OFC generator consists of a single PolM and a Mach–Zehnder Interferometer (MZI). Flat OFCs with up to 11 comb-lines can be generated by the first-stage OFC generator, which is better than most of the previously reported schemes based on a single modulator. To further increase the number of comb-lines, a second-stage OFC generator is followed based on another PolM. The obtained number of comb-lines can be

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increased by a factor of n (n=2, 3, and 5). The simulation and experiment results can verify the good performance of the proposed two-stage OFC generator, which is a cost-effective way to generate a large number of flat comb-lines.

2. Operation principle

Fig. 1 shows the schematic diagram of the proposed two-stage OFC generator, of which the first-stage is used to generate a flat OFC with a comb-line spacing of Δf and a comb-line number of m, and the second-stage is to increase the comb-line number by a factor of n. The first-stage OFC generator consists of a PolM (PolM1), two polarization controllers (PC1 and PC2), a polarization beam splitters (PBS1), a radio frequency source (RF1) and an MZI. The polarization state of the input CW light from the TLS is adjusted by PC1 to have an angle of 45° to one principal axis of PolM1, which is driven by RF1 with a frequency of Δf. At the output of PolM1, a pair of complementary phase-modulated optical signals is generated along the two principal axes (x and y). The normalized optical field can be expressed as

$$\begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} \propto \frac{\sqrt{2}}{2} \begin{bmatrix} \exp(j\omega_c t + j\beta \cos \omega_m t + j\phi) \\ \exp(j\omega_c t - j\beta \cos \omega_m t) \end{bmatrix} \tag{1}$$

where ω_c and ω_m are the angular frequencies of the light source and RF1, respectively, β is the phase modulation index defined as $\beta = \pi V_m / V_\pi$, where V_π is the half-wave voltage of the PolM and V_m is the amplitude of the RF signal, ϕ is the static phase difference between E_x and E_y which can be tuned by changing the bias voltage of PolM1. After PolM1, the optical signal is passed through PC2 before sent to PBS1 to perform polarization-modulation to intensity-modulation conversion. Based on the Jacobi–Anger expansions, the optical field at one output port of PBS1 is

$$\begin{aligned} E &\propto \exp(j\omega_c)[\exp(j\beta \cos \omega_m t + j\phi)\cos \alpha \\ &\quad + \exp(-j\beta \cos \omega_m t)\sin \alpha] \\ &= \exp(j\omega_c) \sum_{k=-\infty}^{+\infty} J_k(\beta)\exp(jk\omega_m) \\ &\quad \times [\exp(j\phi)\cos \alpha + (-1)^k \sin \alpha] \end{aligned} \tag{2}$$

where J_k denotes the kth order of the first kind Bessel function, and α is the angle between the principal axis of PBS1 and the principal axis of PolM1 which can be adjusted by tuning PC2. After separating the even-order sidebands from the odd-order sidebands, Eq. (2) can be expressed as

$$E \propto \exp(j\omega_c) \begin{Bmatrix} \sum_{n=-\infty}^{+\infty} J_{2n}(\beta)\exp(j2n\omega_m) \times [\exp(j\phi)\cos \alpha + \sin \alpha] + \\ \sum_{n=-\infty}^{+\infty} J_{2n+1}(\beta)\exp[j(2n+1)\omega_m] \\ \times [\exp(j\phi)\cos \alpha - \sin \alpha] \end{Bmatrix} \tag{3}$$

According to Eq. (3), if α and ϕ are given, the amplitude difference between the even-order sidebands and the amplitude difference between the odd-order sidebands are determined by $J_{2n}(\beta)$ and $J_{2n+1}(\beta)$, respectively. By adjusting the power of RF1, both $J_{2n}(\beta)$ and $J_{2n+1}(\beta)$ can be changed, and the power flatness of the even-order sidebands and of the odd-order sidebands can be tuned accordingly. Table 1 shows the simulated power flatness of the even-order sidebands and the power flatness of the odd-order sidebands, respectively, for certain values of β when considering different number of total sidebands. The simulation is implemented through Matlab software and the optical carrier is treated as the 0th-order sideband. The results are obtained after optimizing β to obtain a small and comparable flatness for both the even-order and the odd-order sidebands simultaneously. In

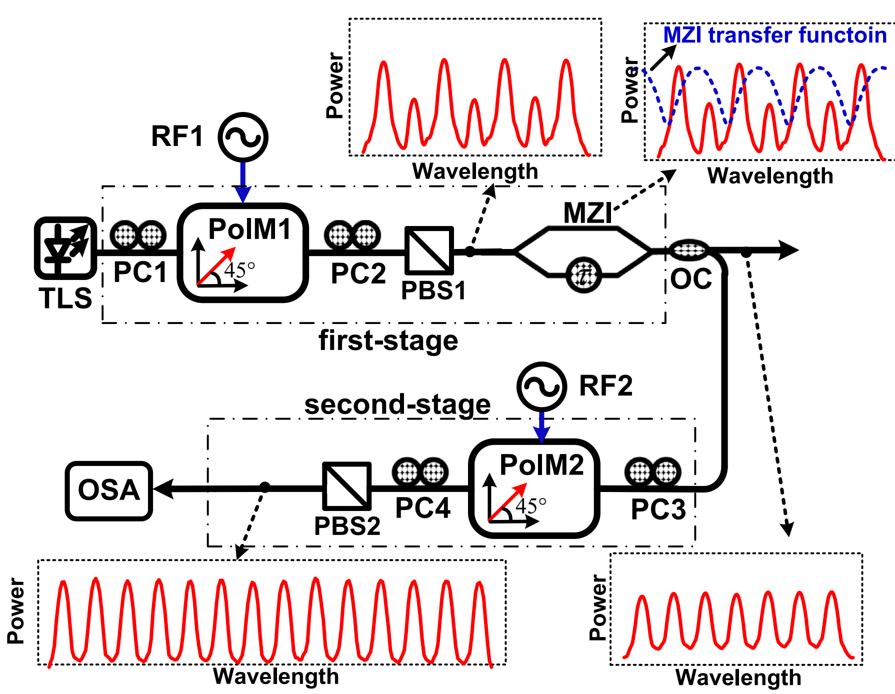

Fig. 1. Schematic diagram of the proposed two-stage OFC generator. (Inset pictures are the spectra at different points and the spectral response of the MZI.)

Table 1
Simulation results of power flatness of the even-order and the odd-order sidebands.

Number of the total sidebands	β	Flatness of the even-order sidebands (dB)	Flatness of the odd-order sidebands (dB)
7	5.32	1.23	1.02
9	6.67	2.38	1.92
11	7.99	3.93	4.00

Table 1, the flatness of both the even-order and the odd-order sidebands becomes worse as the number of total sidebands increases. By selecting a proper β, the group of even-order sidebands and the group of odd-order sidebands are respectively of similar powers, but the power difference between the two sideband groups determined by $J_{2n}(\beta)$ and $J_{2n+1}(\beta)$ is still considerable. To obtain a flat OFC, the output signal from PBS1 is sent to the MZI which serves as a comb filter with a power transfer function of

$$H(f) = \frac{1}{2}\left[1 - \cos\left(2\pi\frac{f}{f_{FSR}}\right)\right] \tag{4}$$

where f is the frequency of the input optical signal, and f_{FSR} is the free spectrum range (FSR) determined by the time delay τ between the two arms of the MZI ($f_{FSR}=1/\tau$). When f_{FSR} is set to twice the frequency of RF1, by tuning the wavelength of the TLS, the power difference between the group of even-order sidebands and the group of odd-order sidebands can be adjusted by the slop of the MZI transfer function. After selecting a proper wavelength to let the low power sideband group undergoes a higher transmission compared with the high power sideband group, the power of the two sideband groups can be adjusted to a very close level and an

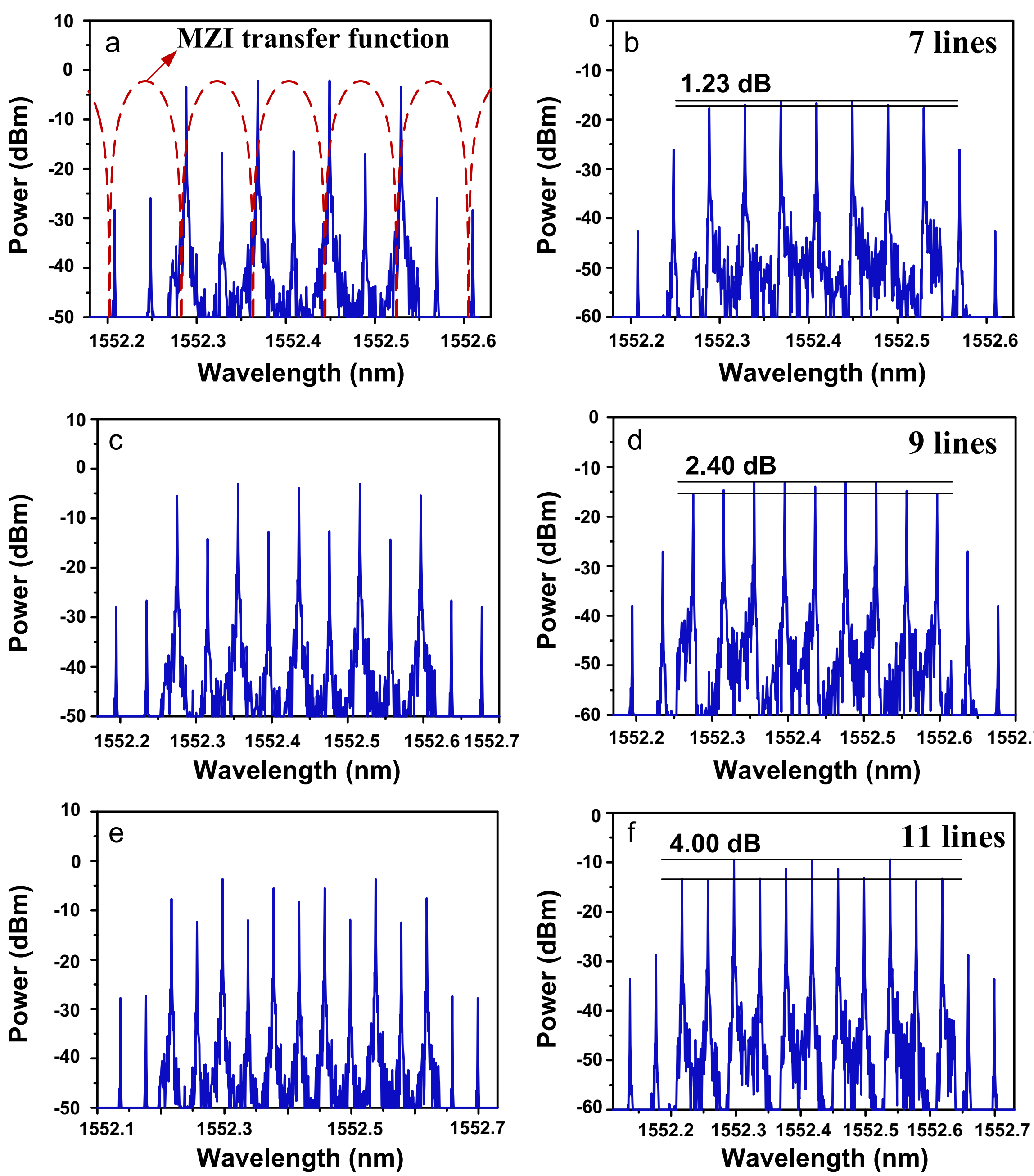

Fig. 2. Simulation results of the first-stage OFC: (a, c and e) the optical spectra before the MZI for generating OFCs with 7, 9 and 11 comb-lines; (b, d and f) the spectra of the generated OFC.

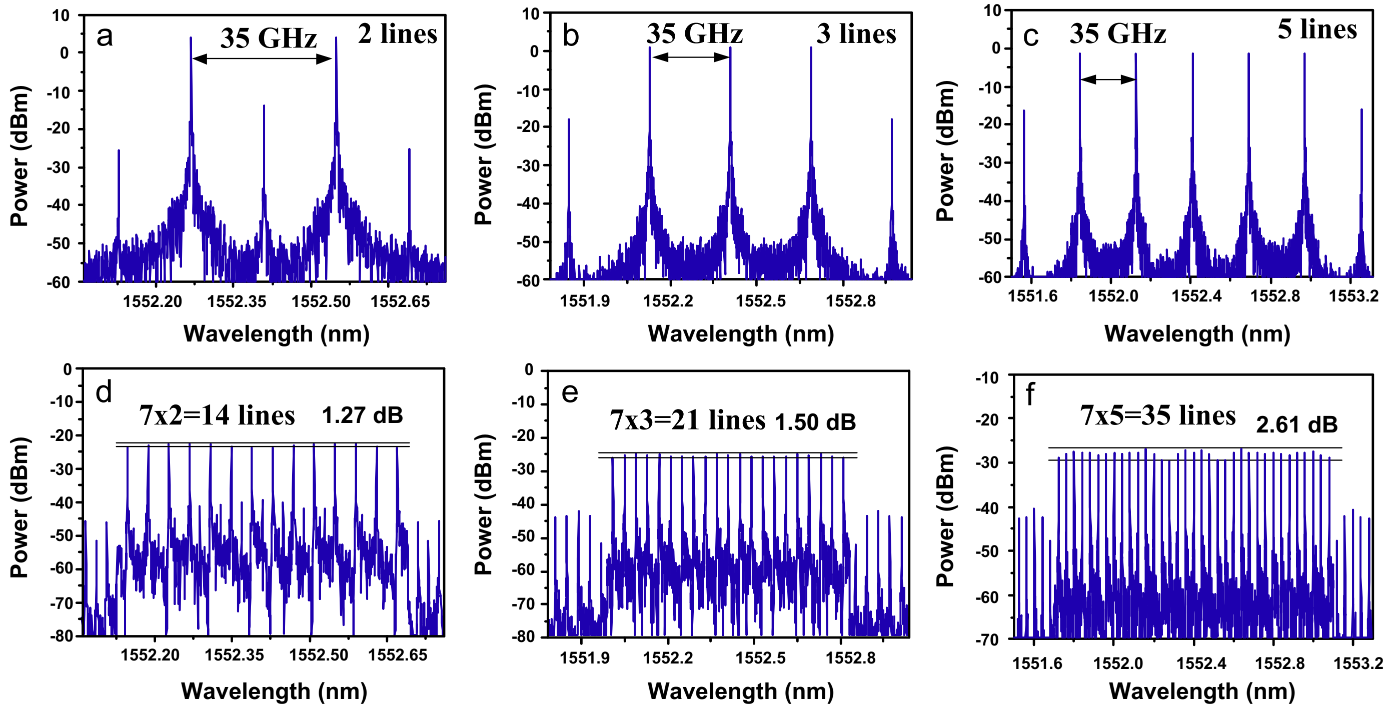

Fig. 3. (a, b and c) The simulated spectra of OFCs with 2, 3, and 5 comb-lines generated by the second-stage OFC generator. (d, e and f) The OFCs with 14, 21 and 35 come-lines by the proposed two-stage OFC generator when the first-stage OFC has 7 comb-lines.

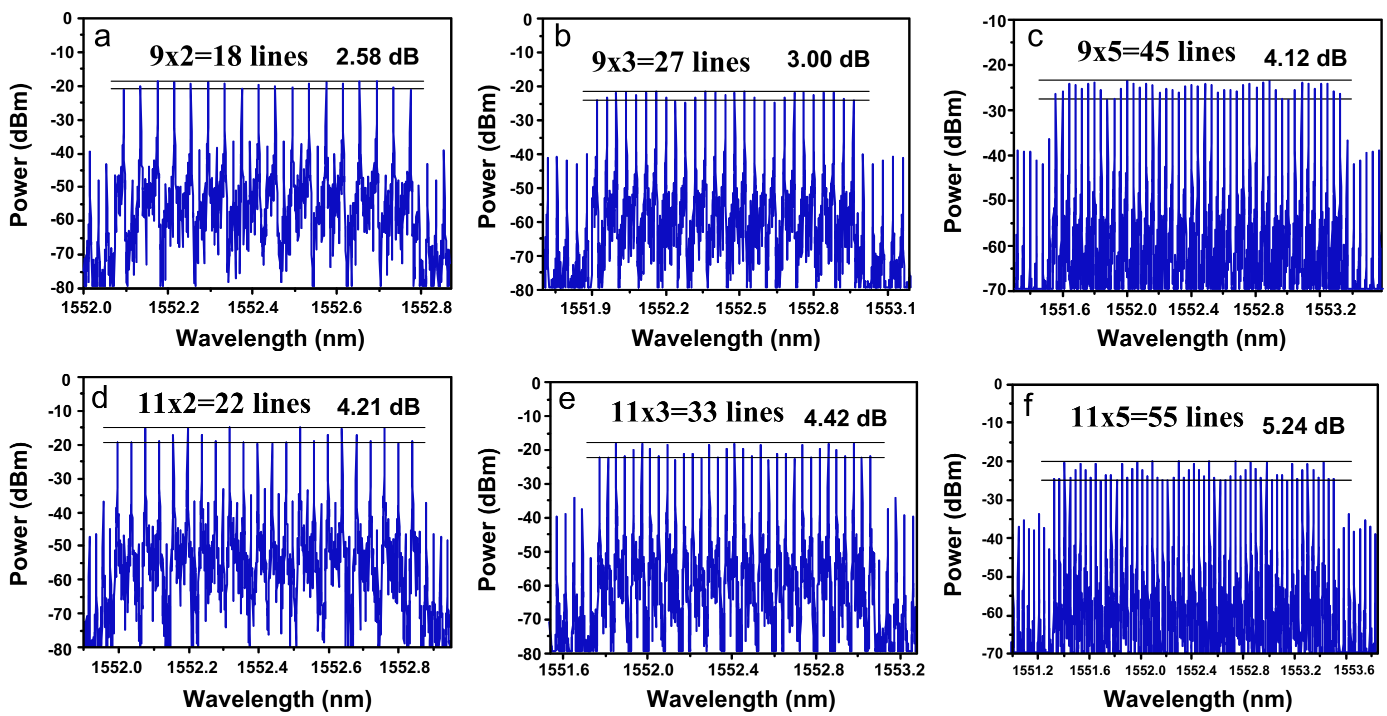

Fig. 4. (a, b and c) The simulated spectra of OFCs with 18, 27, and 45 comb-lines when the first-stage OFC has 9 comb-lines. (d, e and f) The spectra of OFCs with 22, 33, and 55 comb-lines when the first-stage OFC has 11 comb-lines.

OFC with good flatness and increased come-lines can be obtained, as illustrated in Fig. 1.

To further increase the number of comb-lines, a second-stage OFC generator is constructed using another PolM (PolM2), two PCs (PC3 and PC4) and a PBS (PBS2). In the second-stage OFC generator, PolM2 is driven by RF2 with a proper frequency, and the scheme is similar with the polarization-modulation to intensity-modulation conversion in the first-stage OFC generator. If a CW light is sent to the second-stage OFC generator, after properly setting the power of RF2 and the angle between the principal axis of PolM2 and those of PBS2, a flat OFC with n (n=2, 3 or 5) comb-lines can be generated. Here, the two-line OFC is generated based on optical carrier-suppressed modulation [14], and the three- or five-line OFC is generated by properly setting the modulation index and the polarization states before and after PolM2 [9]. When the first-stage OFC (the comb-line spacing is Δf) is sent to the

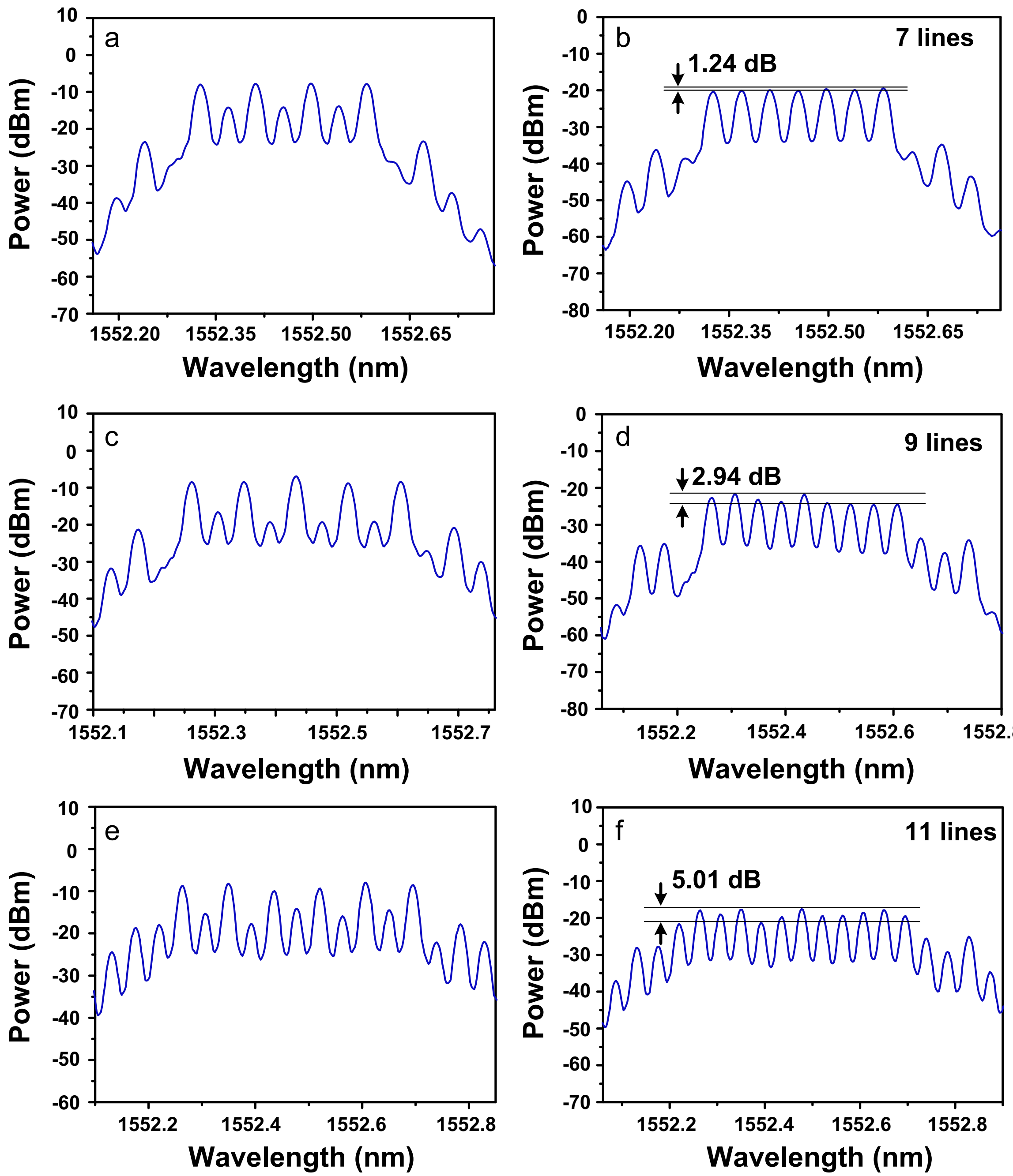

Fig. 5. Experimental results for generating the first-stage OFC with 5.45 GHz comb-line spacing: (a, c and e) the optical spectra before the MZI for generating OFCs with 7, 9 and 11 lines, and (b, d and f) generated OFCs, respectively.

second-stage OFC generator which has a comb-line spacing of $m\Delta f$ (m is the comb-line number of the first-stage OFC), an OFC with a comb-line spacing of Δf and a comb-line number of mn are finally generated, i.e., the comb-line number is increased by a factor of n.

3. Simulation

To investigate the performance of the proposed OFC generator, a simulation is performed using the Optiwave Software (Optisystem 7.0). In the simulation, the frequency of RF1 is 5 GHz, thus the first-stage OFC is spaced by 5 GHz. V_π of the two PolMs is 3 V. To generate OFCs with 7, 9 and 11 comb-lines, the amplitude of RF1 is set to 5.02 V, 6.49 V and 7.63 V, respectively, and the corresponding modulation index is 5.26, 6.79 and 7.99. The optical spectra measured before the MZI for generating OFCs with 7, 9 and 11 comb-lines are shown in Fig. 2(a), (c) and (e), respectively. As can be seen in Fig. 2(a), (c) and (e), a group of even-order sidebands with similar power and a group of odd-order sidebands with similar power are generated. However, the power difference between the two groups is still considerable, e.g., ~13 dB power difference is observed in Fig. 2(a). The MZI has a time delay of 100 ps between the two arms and the corresponding FSR is 10 GHz. The transfer function of the MZI is included In Fig. 2(a). By tuning the wavelength of the laser source, the power difference between the two sideband groups can be tuned to a minimum value after the MZI, and a flat OFC is generated thereafter. It should be noted that, the power difference between the two sideband groups is not the same in Fig. 2(a), (c) and (e), thus the transmission values of the two sideband groups at the MZI are also

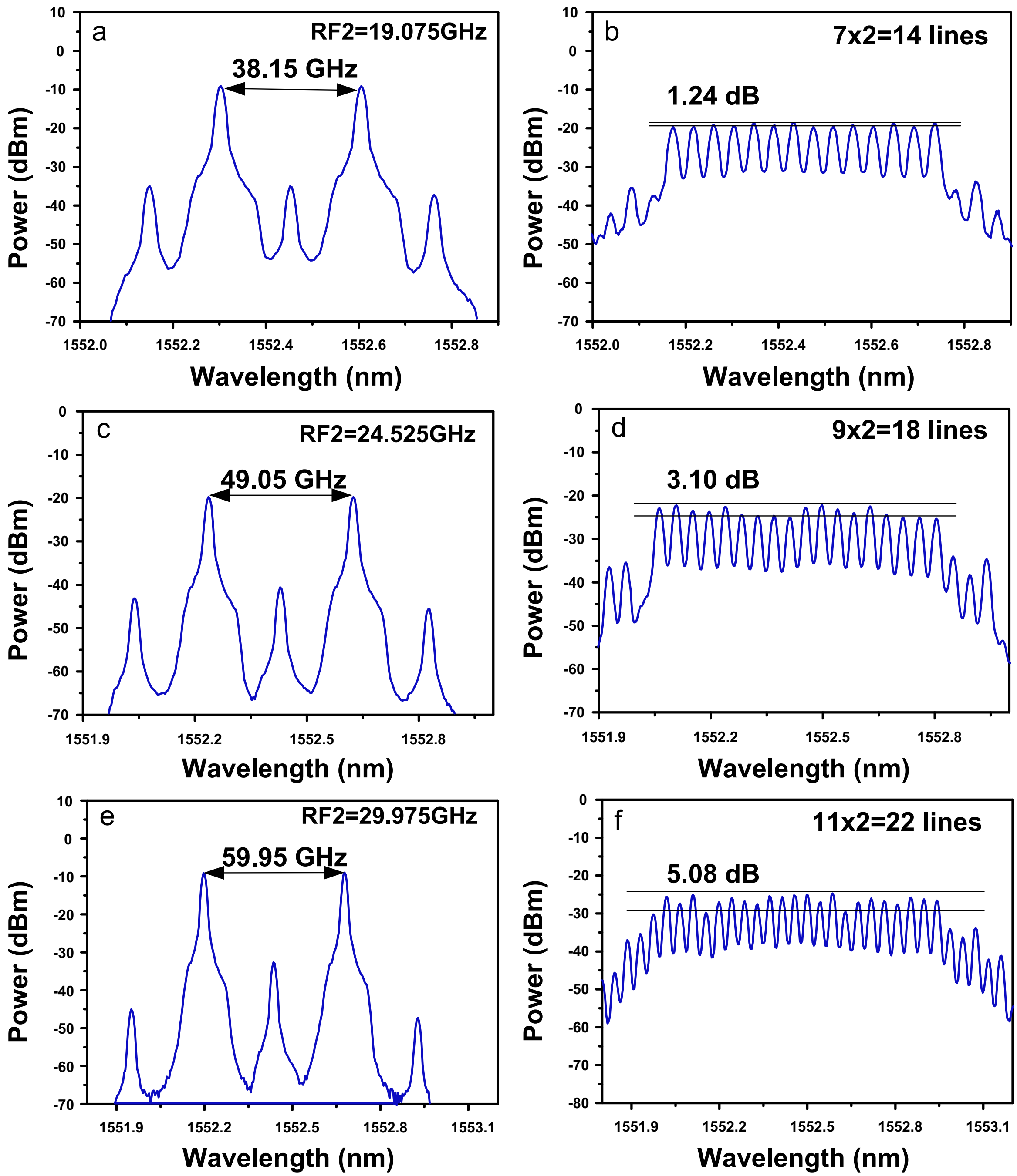

Fig. 6. (a, c and e) The measured optical spectra of the two-line OFCs generated by the second-stage OFC generator only. (b, d and f) The spectra of the OFCs generated by the proposed two-stage OFC generator.

different when generating OFCs with different comb-lines. In the simulation, the wavelengths of the light sources for generating OFCs with 7, 9 and 11 comb-lines are tuned to 1552.408 nm, 1552.436 nm and 1552.417 nm, respectively, and the spectra of the generated OFCs are shown in Fig. 2(b), (d) and (f). The power flatness of the OFCs is 1.23 dB, 2.40 dB and 4 dB, respectively, which is determined by the poorer flatness between the even-order sideband group and the odd-order sideband group before the MZI.

Then, the second-stage OFC generator is investigated. A two-line OFC is generated by optical carrier-suppressed modulation, as shown in Fig. 3(a). In this case, RF2 has a frequency of 17.5 GHz and an amplitude of 1.68 V ($\beta=1.76$), and the angle between the principle axis of PolM2 and those of PBS2 is adjusted to 140°. To obtain the three-line and the five-line OFCs in Fig. 3(b) and (c), the frequencies of RF2 are both 35 GHz, and the amplitudes are 1.18 V ($\beta=1.24$) and 2.44 V ($\beta=2.68$), respectively. Meanwhile, the angle between the principle axis of PolM2 and those of PBS2 is adjusted to 130° and 30°, respectively. In Fig. 3(a)–(c), the comb-line spacing is 35 GHz and an ideal flatness of zero dB is achieved. When the first-stage OFC with 7 comb-lines is sent to the second-stage OFC generator, OFCs with 14, 21 and 35 lines are generated, as shown in Fig. 3(d), (e) and (f), where the power flatness is 1.27 dB, 1.50 dB and 2.61 dB, respectively. Here, the flatness is a little degraded compared with that of the first-stage OFC in Fig. 2 (b) because of the interference between the main lines of the first-stage OFC and the leaked spectral lines outside the main band of the OFC. Similarly, when the first-stage OFC has 9 comb-lines,

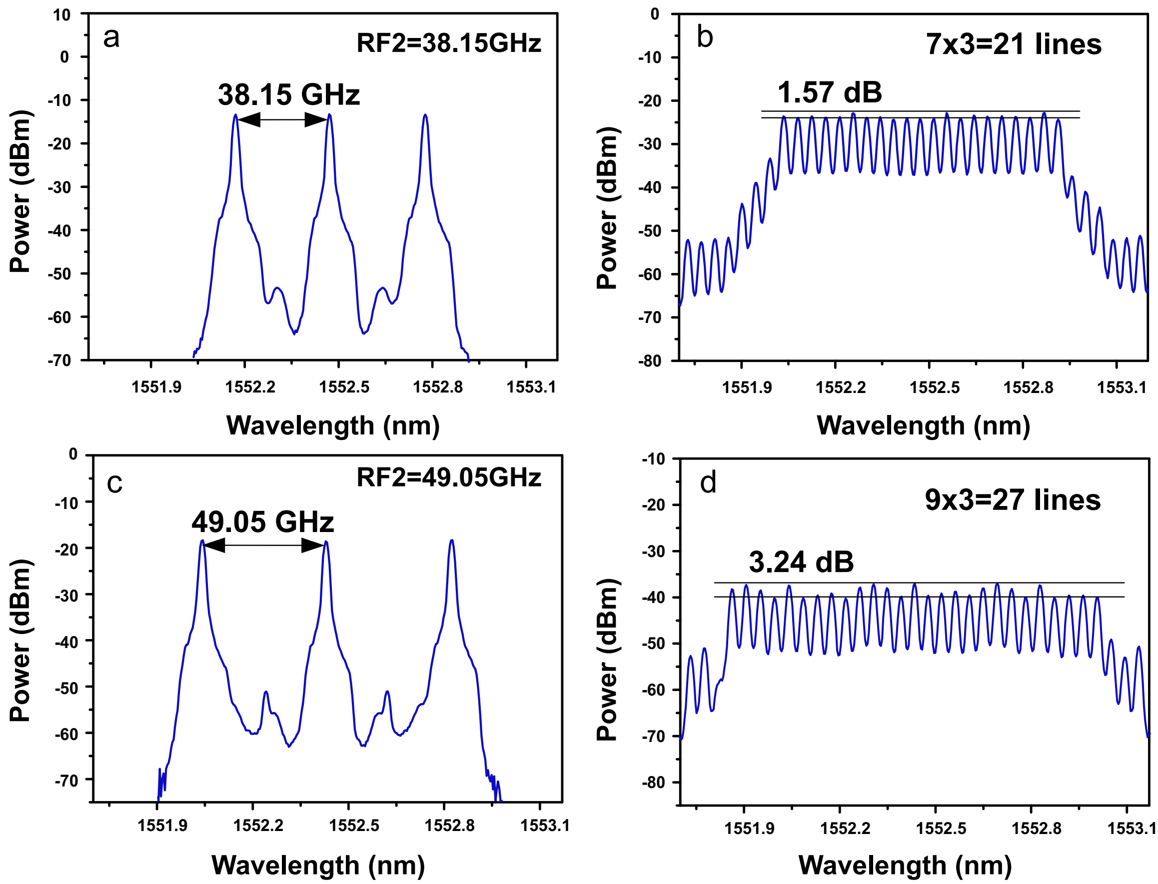

Fig. 7. (a, c) The measured optical spectra of the three-line OFCs generated by the second-stage OFC generator only. (b, d) The spectra of the OFCs generated by the proposed two-stage OFC generator.

OFCs with 18, 27 and 45 comb-lines can be generated with a flatness of 2.58 dB, 3 dB and 4.12 dB, as shown in Fig. 4(a), (b) and (c), respectively. If the first-stage OFC has 11 comb-lines, OFCs with 22, 33 and 55 comb-lines are obtained, and the flatness is 4.21 dB, 4.42 dB and 5.24 dB, as shown in Fig. 4(d)–(f). Again, the power flatness in Fig. 4 is degraded compared with that of the corresponding first-stage OFC.

4. Experimental results and discussion

An experiment based on the setup in Fig. 1 is carried out. The TLS (Agilent N7714A) has an output power of 16 dBm and its frequency can be tuned by a step of 0.1 GHz. The two PolMs (Versawave Inc.) both have a bandwidth of 40 GHz and a half-wave voltage of 3.5 V at 1 GHz. The two driving signals (RF1 and RF2) are generated by two vector signal generators (Agilent E8257D & E8257D). The PBS has a polarization extinction ratio of more than 35 dB. An optical spectrum analyzer (OSA) with a resolution of 0.02 nm is used to monitor the optical spectrum. The MZI is made by splicing two 3-dB optical couplers with a time delay between the two interference arms. By controlling the time delay between the two arms, an MZI with a specific f_{FSR} can be obtained. To stabilize the transfer function of the MZI, the experiment is performed in a room with near constant temperature, and the MZI is put inside a box made by foam rubber to resist the mechanical vibration. No apparent shift of the MZI transfer function is observed during the experiment. To achieve better stability and to reduce the system volume, an MZI made on a planar lightwave circuit (PLC) can be applied.

Fig. 5 shows the experimental results for generating the first-stage OFC with a comb-line spacing of 5.45 GHz. The frequency of RF1 is 5.45 GHz and the MZI has an FSR of 10.9 GHz. When the power of RF1 is set to 21.5, 24.3 and 26.6 dBm, three OFCs with 7, 9 and 11 comb-lines are generated, respectively. The optical spectra measured before the MZI are shown in Fig. 5(a), (c) and (e), and the spectra of the generated OFCs are shown in Fig. 5(b), (d), and (f), respectively. As shown in Fig. 5, the group of even-order sidebands and the group of odd-odder sidebands can be tuned to nearly the same level respectively before the MZI, and the filtering effect of the MZI can adjust the flatness of the whole spectrum. The power variation of the obtained three OFCs in Fig. 5(b), (d), and (f) is 1.24, 2.94 and 5.01 dB, respectively, which is close to the simulation results. The power loss of the first-stage OFC generator is measured to be 18.8 dB, 14.2 dB and 11.6 dB for generating OFCs with 7, 9 and 11 comb-lines, respectively. Here, the loss is different because the MZI introduces different power transmissions for the two sideband groups when generating OFCs with different come-lines.

Fig. 6(a), (c) and (e) show the two-line OFCs generated by the second-stage OFC generator, where the comb-line spacing is 38.15 GHz, 40.09 GHz and 59.95 GHz, i.e., the come-line spacing is 7, 9 and 11 times of that of the first-stage OFC and the corresponding frequency of RF2 is 19.075 GHz, 24.525 GHz and 29.975 GHz, respectively. When the first-stage OFCs with 7, 9 and 11 comb-lines are sent to the second-stage OFC generator of which the comb-line spacing is 38.15 GHz, 49.05 GHz and 59.95 GHz, respectively, OFCs with 14, 18 and 22 comb-lines are generated, as shown in Fig. 6(b), (d) and (f). The flatness of the three OFCs in Fig. 6(b), (d) and (f) is 1.24 dB, 3.10 dB, 5.08 dB, respectively, which is a little degraded compared to that of the corresponding first-stage OFC. Fig. 7(a) and (c) show the three-line OFCs

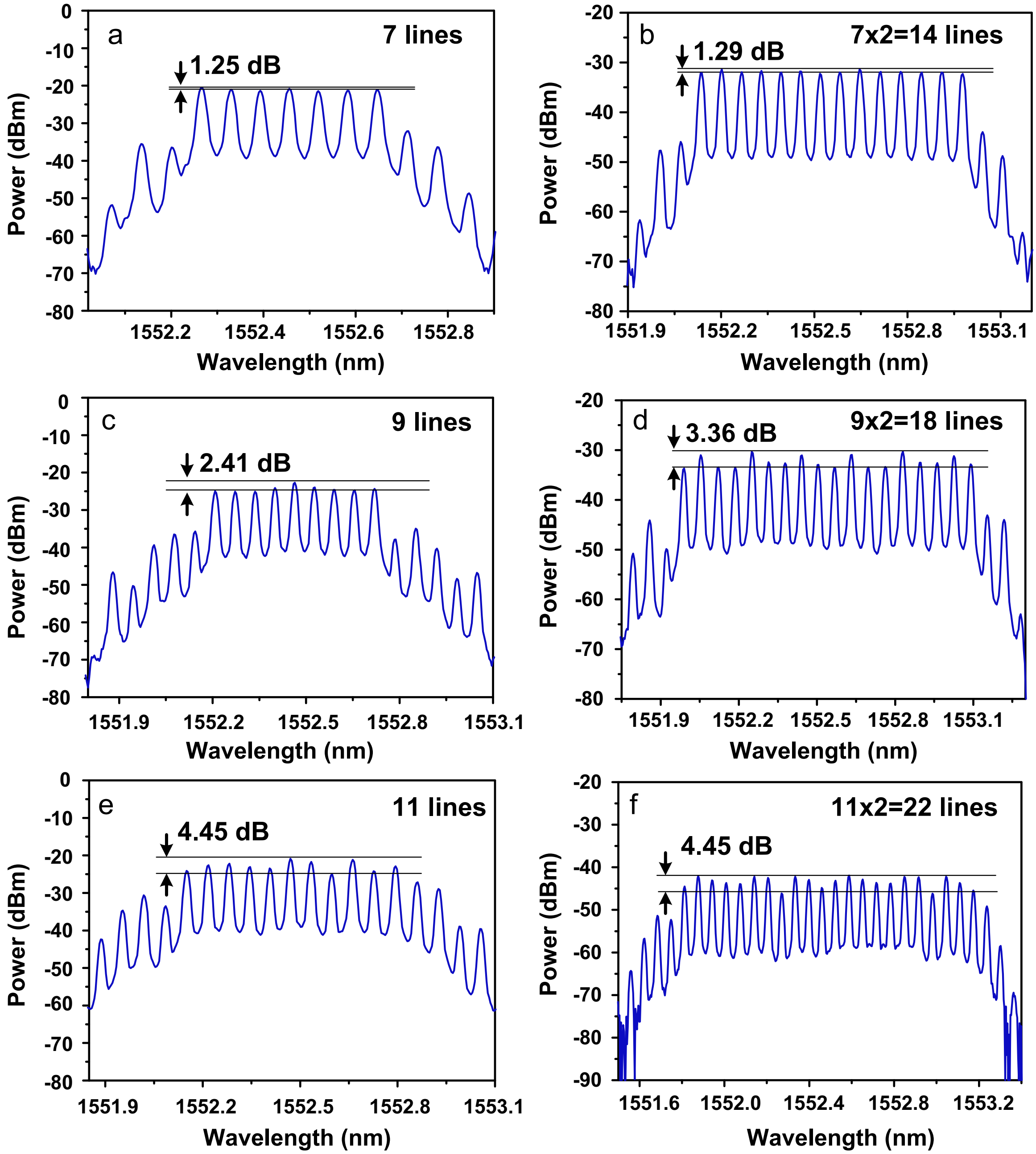

Fig. 8. Experimental results for generating OFCs with 8.05 GHz comb-line spacing: (a, c and e) the spectra of the first-order OFCs with 7, 9, and 11 comb-lines, respectively; (b, d and f) the OFCs generated by the proposed two-stage OFC generator with 14, 18 and 22 comb-lines, respectively.

generated by the second-stage OFC generator, where the comb-line spacing and the frequency of RF2 are 38.15 GHz and 49.05 GHz, respectively. When the first-stage OFCs with 7 and 9 comb-lines are sent to the second-stage OFC generator with a comb-line spacing of 38.15 GHz and 49.05 GHz, respectively, OFCs with 21 and 27 comb-lines are generated, as shown in Fig. 7(b) and (d), where the flatness is 1.57 dB and 3.24 dB, respectively. The power loss of the second-stage OFC generator is measured to be 12.4 dB and 14.1 dB for generating the two-line and three-line OFCs, respectively. In the experiment, an EDFA is inserted between the two stages to compensate the loss. Due to the lack of high frequency electrical simplifiers, the generation of OFCs with 33, 35, 45 and 55 comb-lines are not demonstrated in the experiment.

To test the frequency tunability of the proposed OFC generator, FSR of the MZI is tuned to 16.1 GHz by changing the time delay τ of the MZI and RF1 is tuned to 8.05 GHz, accordingly. Fig. 8(a), (c) and (e) show the optical spectra of the first-stage OFCs with 7, 9, and 11 comb-lines, where the flatness is 1.25 dB, 2.41 dB and 4.45 dB, respectively. Then, a second-stage OFC generator which can generate two-line OFCs with comb-line spacing of 56.35 GHz, 72.45 GHz and 88.55 GHz is followed, and the corresponding frequency of RF2 is 28.175 GHz, 36.225 GHz and 44.275 GHz respectively. Fig. 8(b), (d), and (f) show the spectra of the generated 8.05 GHz spaced OFCs with 14, 18 and 22 comb-lines, where the flatness is 1.29 dB, 3.36 dB and 4.45 dB, respectively. These results also agree well with the simulation results.

5. Conclusions

We have proposed a two-stage OFC generation scheme based on two PolMs and an MZI. In the first-stage OFC generator, by adjusting the power difference between the group of even-order sidebands and the group of odd-order sidebands using the MZI, OFCs with up to 11 comb-lines can be generated, which not only benefits from increased number of comb-lines compared to the previous schemes based on a single modulator, but also benefits from low complexity and cost. Using a second-stage OFC generator, the comb-line number can be further increased by a factor of 2, 3 and 5, respectively. Performance of the proposed OFC generator is investigated through both simulations and experiments. OFCs with up to 55 comb-lines can be generated by the proposed two-stage OFC generator, which can be utilized in optical signal processing, precise optical metrology and so on.

Acknowledgments

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