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Power efficient ultraflat optical frequency comb generation by cascading modulators

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Abstract. A power efficient optical frequency comb (OFC) is highly desired for applications with limited power supply, e.g., microwave photonics applications in moving vehicles. An ultraflat OFC generation is demonstrated with 0.19-dB flatness, 15 comb lines, and 18.3-dBm total RF power consumption. The scheme is based on spectral convolution. A five-line comb with 0.06-dB flatness and 4.0-GHz spacing is first generated in an intensity modulator. Then the signal is injected to a phase-modulator driven by ×5 frequency of 20.0 GHz to obtain the ultraflat 15-line comb with 0.19-dB flatness. The comb spacing is adjustable by controlling the input frequency of microwave source within the bandwidth of phase-modulation. Our work demonstrates a power efficient approach to obtain ultraflat comb and may benefit microwave photonics applications requiring low-power consumption. [DOI: 10.1117/1.OE.56.10.106115]

Keywords: modulator; optical frequency comb; microwave photonics.

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1 Introduction

Optical frequency comb (OFC) generation has been researched for years because of its wide applications in optical communication,[1–3] distance measurement,[4] arbitrary waveform generation,[5] and microwave photonics.[6,7] In general, there are many methods that can be used to generate OFC, such as mode-locked lasers,[8] recirculating frequency shifter,[9–12] nonlinear optical fiber,[13,14] and cascaded modulators.[15–24] Among these methods, OFC generation by cascaded modulators has attracted much attention for its simple configuration, flexibly tunable comb spacing, and high flatness. Many researchers have applied different kinds of cascaded modulators to generate flat OFC, including one Mach–Zehnder modulator (MZM) and two phase-modulators (PM),[25] one MZM and one PM,[15–18,26,27] two polarization modulators (PolMs),[19] two MZMs,[20] and one PM and one PolM.[28] In addition, OFC generation by a single modulator has also been reported.[29–31]

However, nearly all the above-mentioned works utilize the nonlinear modulation of the modulators to generate OFC. That is, in addition to the first-order sidebands generated by the radio-frequency (RF) modulation, more high-order sidebands are also generated. To achieve this, a very high modulation index must be realized, which leads to a very high RF power consumption up to 30 dBm. This is not desired for practical applications with limited power supply, e.g., to be a frequency comb source for microwave photonics applications used on moving vehicles. Moreover, OFC generated by this nonlinear modulation technique usually has a flatness of ∼1 dB limited by the nonlinear response of modulators and nonideal modulation waveforms. In many spectrum-processing-related applications, an even flatter OFC is desired. For example, microwave synthesis by filtering and beating two comb lines requires equal power of two comb lines to maximize the beating efficiency. Arbitrary waveform generation by attenuating power and tuning phase of each comb line also requires flat comb lines to reduce power penalty and increase signal-to-noise ratio.

In this paper, we explore the power efficient ultraflat OFC generation from a quasilinear modulation scheme of two cascaded modulators. In our design, only first-order sidebands are required in the modulation (quasilinear modulation) and no high-order sidebands are needed, which significantly reduces the requirement on the RF power consumption and also improves the flatness of the generated OFC. By combining fundamental modulation RF and its ×2 and ×5 harmonic frequencies, and precisely balancing their power, an OFC with only 0.19-dB power variation and 15 comb lines has been generated. Total RF power consumption is only 18.3 dBm. The MZM and PM used in our design are commercially available ones with a V_π near 5 V and 3.2 V. In addition, OFC with different spacing can be obtained by changing the modulation frequency. Therefore, our work has demonstrated an ultraflat OFC with very low RF power consumption and cost, and may benefit the microwave photonics applications with limited power supply and requiring high comb flatness.

2 Experimental Results

The experimental setup and principle to generate a power efficient ultraflat OFC are shown in Figs. 1(a) and 1(b), respectively. The setup consists of a continuous wave (CW) laser near 1550 nm, a $LiNbO_3$ MZM (Optilab IM-1550-PM-12), and a $LiNbO_3$ PM (EOspace PM-5S5-20-PFA-PFA-UV). The input power of CW laser is 6 dBm. The first MZM is driven by a 4.0 GHz (f_m) RF source and its second harmonic frequency of 8.0 GHz ($2f_m$) simultaneously. The

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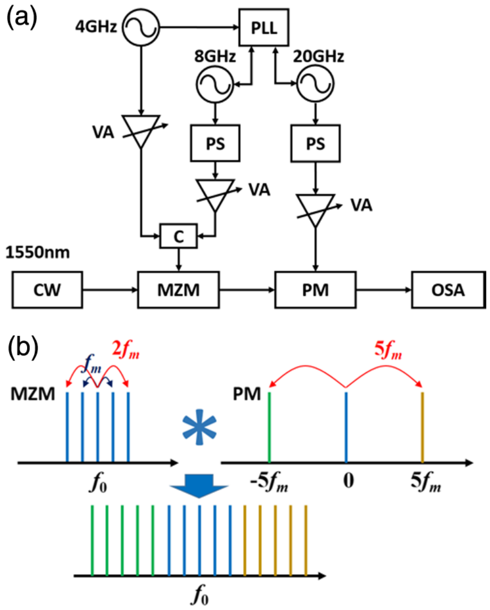

Fig. 1 (a) Experimental setup of power efficient ultraflat OFC generation. VA, variable amplifiers; PS, phase-shifter; C, RF combiner; PLL, phase-locked loop and (b) the principle of producing 15 flat comb lines.

second PM is driven by a ×5 harmonic frequency of 20.0 GHz ($5f_m$). The RF sources of 8.0 and 20.0 GHz are two independent RF oscillators phase-locked to the RF source of 4.0 GHz with two phase-locked loops (PLLs). PLL is a very mature electronic technique and consumes very low power compared with the power consumption of RF oscillators. The output of OFC is characterized by an optical spectrum analyzer (OSA, AQ6370D) with a resolution of 0.02 nm and an averaging time of 10 ms. As shown in Fig. 1(b), in the first MZM, 4.0 and 8.0 GHz frequencies generate five flat comb lines with 4.0 GHz spacing by quasilinear modulation. That is, each frequency only mainly generates two first-order sidebands and no second-order sideband is required. This leads to a very low requirement on the injected RF power and V_π of MZM. By balancing the driving power of two frequencies and bias voltage, these five comb lines can be perfectly flat in principle. In the PM, 20.0 GHz ($5f_m$) frequency generates three flat comb lines with 20.0 GHz spacing using a medium-power RF source. The PM also operates in a quasilinear region. The power of first-order sidebands should be equal to that of the center frequency but no second-order sidebands are required. Cascading these two modulators is equivalent to a spectral convolution in frequency domain and thus a flat comb with 15 comb lines can be obtained. The power and phase of three RFs are tuned by electrical variable amplifiers (VAs) and phase-shifters (PSs) to obtain high flatness of OFC.

The mathematical analysis is also performed to better understand the above process. The optical field of the input CW is given by $E_{\text{in}}(t) = E_0 \exp(j2\pi f_0 t)$, where E_0 is the amplitude of optical field and f_0 is the optical carrier frequency. In our experiment, a commercial single-drive MZM is used. The output of MZM can be expressed as $E_{\text{out1}}(t) = E_{\text{in}}(t)\exp(j\varphi_{IM}/2)\cos(\varphi_{IM}/2)$, where φ_{IM} is the phase-change induced by the intensity modulation. It is worth noting that the values of V_π are 5.3 V for RF port and 5 V for bias port, which are different. Two RF signals of different frequencies are combined to drive MZM, so the phase-change φ_{IM} can be described as

$$\varphi_{IM} = \theta + m_1 \cos(2\pi t \cdot f_m) + m_2 \cos(2\pi t \cdot 2f_m + \Delta\varphi_2), \tag{1}$$

where $\varphi = \pi V_{DC}/V_{\pi DC}$ and $V_{\pi DC} = 5$ V denote the phase-shift caused by the DC bias voltage V_{DC}, $m_1 = \pi V_{RF1}/V_{\pi RF}$ and $V_{\pi RF} = 5.3$ V is the RF modulation index of f_m (2.5 GHz), $m_2 = \pi V_{RF2}/V_{\pi RF}$ is the RF modulation index of $2f_m$ (5.0 GHz), and $\Delta\varphi_2$ is the phase-difference of two RF signals. Then, the optical field after PM is given by

$$E_{\text{out2}}(t) = E_{\text{in}}(t)\exp\left(j\frac{\varphi_{IM}}{2}\right)\cos\left(\frac{\varphi_{IM}}{2}\right)\exp(j\varphi_{PM}), \tag{2}$$

where φ_{PM} is the phase-change induced by the phase-modulation and is given by

$$\varphi_{PM} = m_3 \cos(2\pi t \cdot 5f_m + \Delta\varphi_3), \tag{3}$$

where m_3 denotes RF modulation index of $5f_m$ (20.0 GHz) and $\Delta\varphi_3$ is the phase-difference of f_m (4.0 GHz) and $5f_m$ (20.0 GHz) RF signals. With this simple model, the simulation results match well with the experimental output, which will be shown later.

The experimental output spectra of OFC are summarized in Fig. 2. Figure 2(a) shows the output spectrum of MZM. Five comb lines with 4.0 GHz spacing are obtained with a power variation of only 0.06 dB. The inner two comb lines are the first-order sidebands generated by 4.0-GHz modulation and the outer two lines are by 8.0-GHz modulation. The RF power of 4.0 and 8.0 GHz is 11.5 and 10.1 dBm, respectively. The DC bias voltage is 4.8 V. The advantage of this scheme is the usage of commercial standard modulators and low input RF power. Table 1 compares the RF power requirement to generate five flat comb lines using a single-drive or dual-drive MZM. It can be seen that the RF power in our $f_m - 2f_m$ driven scheme is much lower than other two schemes. Adding a $2f_m$ frequency source does not increase much complexity of the setup but benefits the power consumption. A medium-power RF source is also cheaper than a high-power RF amplifier. The output waveform is shown in Fig. 2(c). The output spectrum of PM is shown in Fig. 2(b) and a spectrum in a wider span is shown in Fig. 2(d). The power variation of OFC is only 0.19 dB with a driving RF of 20.0 GHz and a driving RF power of 18.3 dBm. The PM is a commercial product with a V_π of 3.2 V at 1 GHz. The V_π is 4.54 V at 20 GHz and the corresponding modulation index is 1.43. The simulation results are plotted as red dots (power) and blue dots (phase) in Fig. 2(d). It can be observed that the simulation matches well with the experimental results. It should also be mentioned that the OFC visibility (peak to dip) shown in Fig. 2(d) is ~6 dB, which is not limited by the scheme itself but the resolution of OSA. A 4 GHz spacing corresponds to a wavelength spacing of 0.032 nm, which is close to the 0.02-nm resolution of OSA.

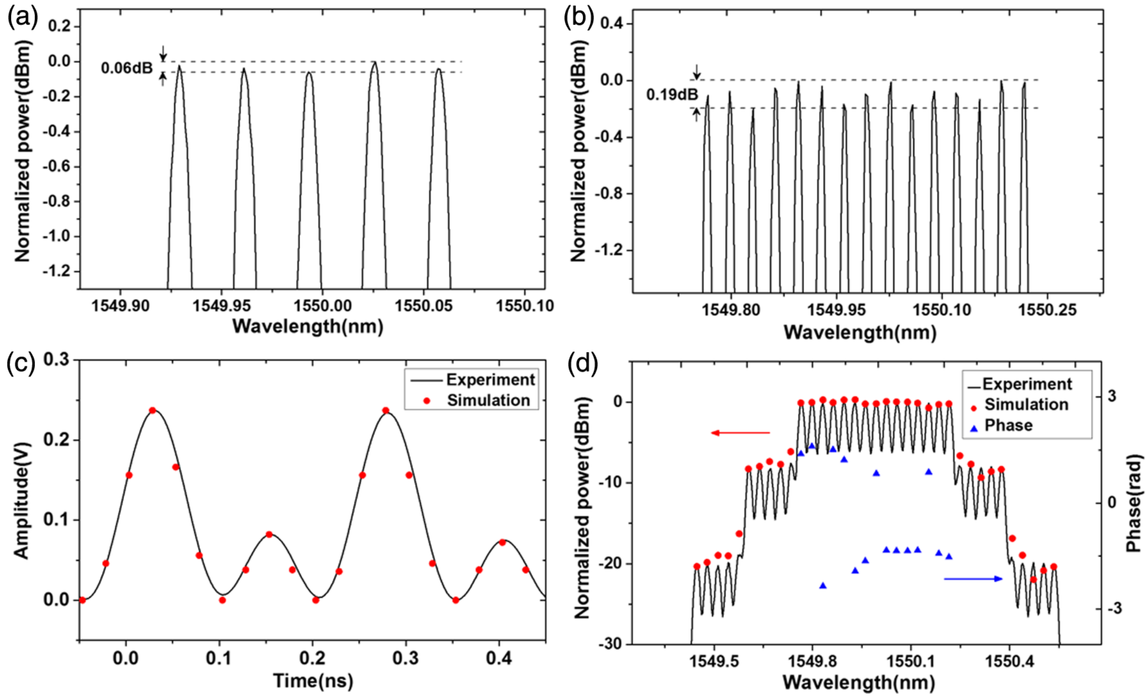

Fig. 2 (a) Experimental output spectrum after MZM, (b) output spectrum after PM, (c) output waveform after PM, experiment (solid line) and simulation (red dots), and (d) output spectrum after PM with a wider span (solid line), simulation power (red dots), and phase (blue dots).

Table 1 Comparison of generating five flat comb lines with fixed V_π of 5.3 V.

Configuration	Frequency	Lines	Injected RF power (dBm)
Single-drive MZM	f_m and $2f_m$	5	13.8
Single-drive MZM	f_m	5	26.8
One dual-drive MZM	f_m	5	21.1

3 Discussion

In Table 2, OFC performances are compared in the specifications of number of lines, flatness, injected RF power, maximum modulation index, and bandwidth for the reported schemes with no more than two modulators. It can be seen that our scheme has significantly improved the flatness of OFC and reduced the RF power consumption by more than 8 dB.

To show the tunability of the OFC spacing, an OFC with same setup and 2.5-GHz spacing is also demonstrated, shown in Fig. 3. The OFC has a flatness of 0.18 dB and a total RF power consumption of ∼19.8 dBm. It should be noted again that the comb visibility (peak to dip) shown in Fig. 3(a) is ∼1.5 dB, which is not limited by the scheme but by the resolution of OSA. Moreover, if a 10-GHz spacing is chosen, a PM with 50-GHz bandwidth is commercially available. A 15-line OFC has a bandwidth of 140 GHz, which is able to support most of the microwave photonics applications.

If the modulation frequency of $5f_m$ exceeds the bandwidth of PM, one may choose a low-order harmonic frequency to drive the PM. Figure 4 demonstrates the possibility of using ×2, ×3, or ×4 harmonic frequency to generate flat OFCs. Figure 4(a) shows the output spectrum of PM driven by an 8.0 GHz ($2f_m$) frequency. An OFC with 0.07-dB flatness and seven comb lines is obtained. Similarly, an OFC with 0.14-dB flatness and nine comb lines is obtained with a driving frequency of 12.0 GHz ($3f_m$) as

Table 2 Comparison on the OFC specifications in different schemes.

Configuration	Number of lines	Flatness (dB)	Injected RF power (dBm)	Max mod. index	Bandwidth (GHz)
Ours	15	0.19	18.3	1.43	56
One dual-drive MZM[29]	11	0.5	32.1	7.5	60
MZM + PM[16]	15	1.0	29.0	9.3	140
PM + PolM[28]	13	2.1	27.8	4.9	120
PolM + PolM[19]	25	0.92	26.2	5.3	96

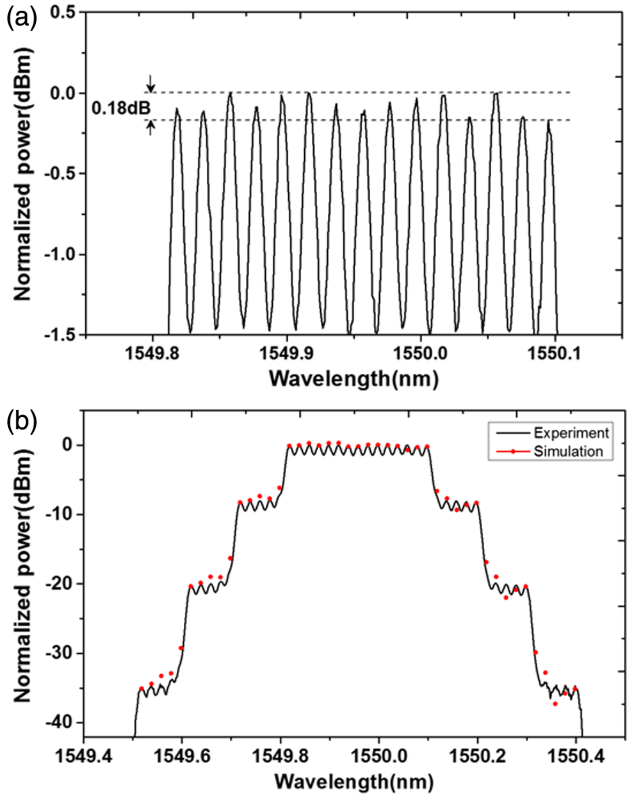

Fig. 3 OFC generation with 2.5 GHz spacing with an OSA span of (a) 0.4 nm and (b) 1.1 nm.

shown in Fig. 4(b). And an OFC with 0.11-dB flatness and 11 comb lines is obtained with a driving frequency of 16.0 GHz ($4f_m$) as shown in Fig. 4(c). Figure 4(d) summarizes the performance of four frequencies (including 20.0 GHz). It is consistent with the previous analysis that $5f_m$ has the best performance of a number of lines in the generated OFC. It should be mentioned that when the driving RF on PM is changed, the optimized driving power of RFs on MZM is also changed accordingly as shown in Table 3.

A question may be raised whether more number of flat comb lines can be generated using a PM so that an even wider OFC can be obtained. In the experiment, it has been demonstrated that three-line ultraflat comb using a PM and a single RF signal can be generated. However, there is no possibility to generate a five-line ultraflat comb with the same setup by increasing RF power. When a PM driven by a sinusoidal RF signal is used to modulate the CW light, the expressions for the first-order, second-order, and third-order can be expressed as $E_0 = EJ_0(m)$, $E_{\pm 1} = EjJ_1(m)\exp(\pm j\omega_s t)$, and $E_{\pm 2} = -EJ_2(m)\exp(\pm j2\omega_s t)$. To obtain a five-line flat comb, we let $|E_0| = |E_{\pm 1}| = |E_{\pm 2}|$ and get $J_0(m) = J_1(m) = J_2(m)$. According to the value of Bessel function of the first kind for $n = 0$, 1, and 2, there does not exist such an m to satisfy this equation. Therefore, in theory, only three-line ultraflat comb can be generated by applying a single RF signal to a PM. If we lose the requirement on the flatness of OFC, an even wider OFC can be obtained by generating more comb lines in the PM, shown in Fig. 5.

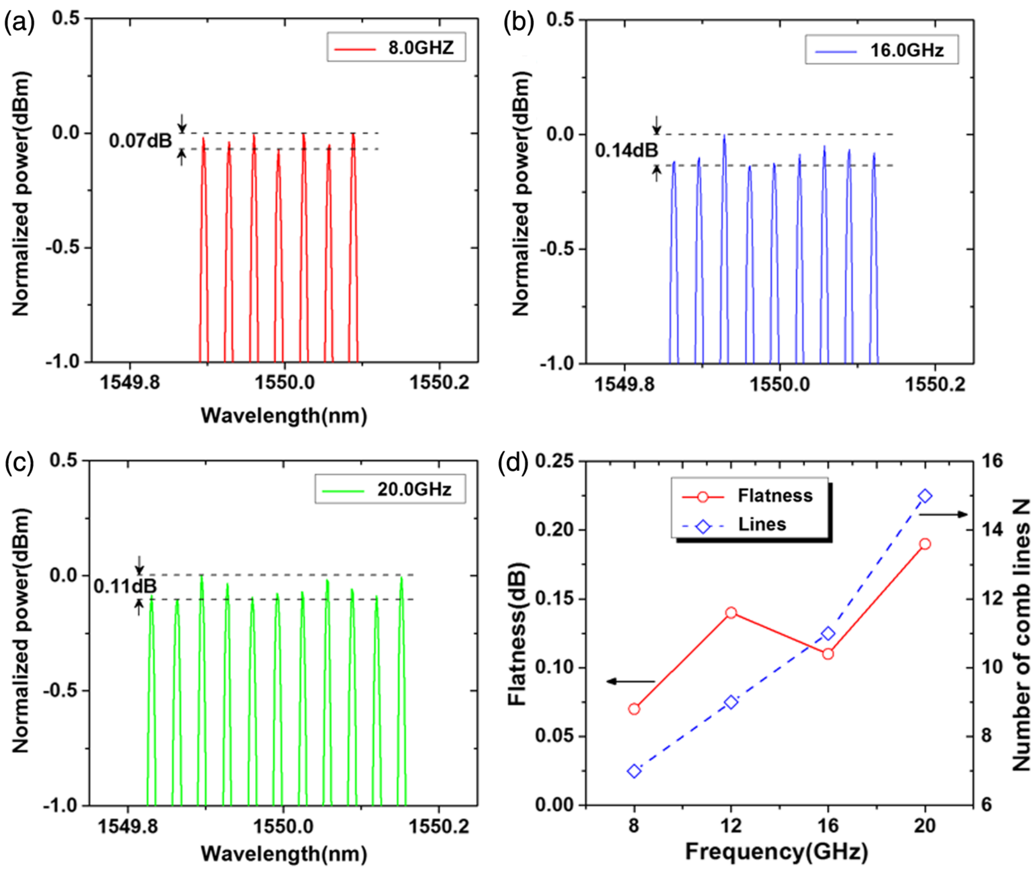

Fig. 4 Experimental OFC spectra of different RFs injected to PM: (a) 8.0 GHz, (b) 12.0 GHz (c) 16.0 GHz, and (d) comparison of four different RFs.

Table 3 The RF power of different frequencies applied for PM.

Freq. on PM	RF power of f_m on MZM (dBm)	RF power of $2f_m$ on MZM (dBm)	RF power on PM (dBm)
$2f_m$	12.5	7.5	16.0
$3f_m$	10.4	0	14.9
$4f_m$	10.9	6.2	15.6
$5f_m$	11.5	10.1	16.3

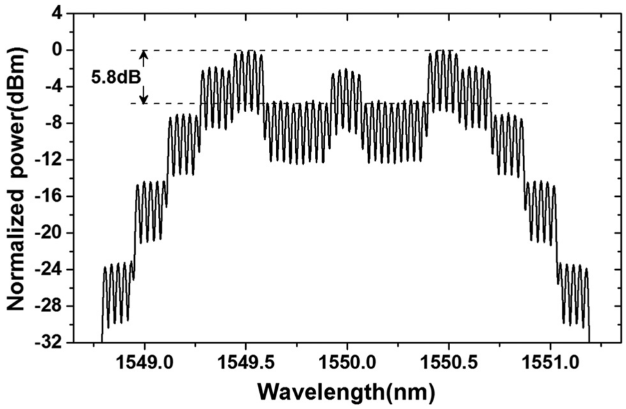

Fig. 5 Generated 45 lines with flatness of 5.8 dB.

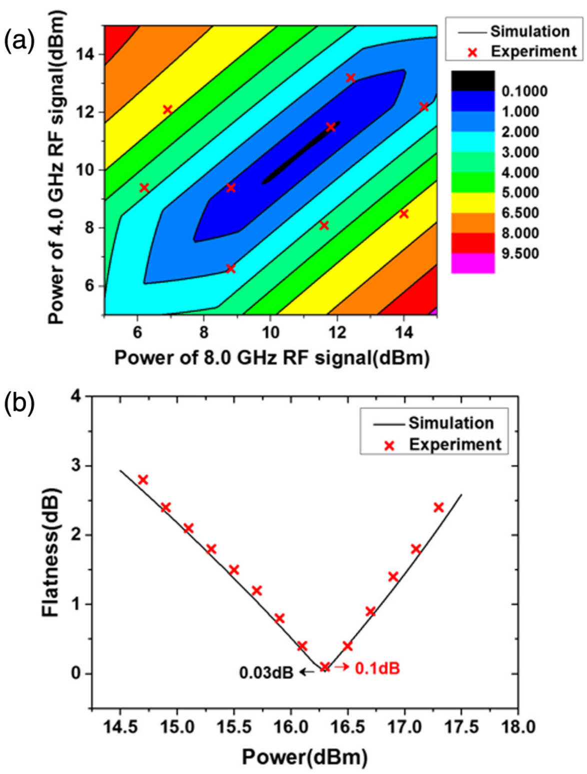

Fig. 6 (a) Simulation and experimental results on the five-line OFC flatness with respect to the power of 4.0- and 8.0-GHz RF signals injected to MZM. (b) Simulation and experimental results on the three-line OFC flatness with respect to the 20.0-GHz RF power injected to PM.

The OFC has 45 lines with a flatness of 5.8 dB generated by increasing the injected RF power to PM to 23.0 dBm.

Here, we put more discussion on the generation of flat 5-line OFC generated by MZM, a simulation is performed and the simulated OFC flatness is shown in Fig. 6(a). The DC bias voltage is unchanged as 4.8 V in the previous experiment. In the black region, the OFC exhibits a flatness of 0.1 dB, and in the dark blue region, the OFC exhibits a flatness of 1 dB. The figure helps to optimize the best RF power to obtain OFCs with high flatness. The red-cross markers on the figure are the experimental data, which match well with the simulation. Figure 6(b) shows the simulation and experimental research on the flatness of generated three comb lines in PM driven by 20.0-GHz RF. This experiment is done by removing the MZM temporarily. From the figure, it indicates the possibility to obtain three comb lines with a variation <0.1 dB. Since there is no DC bias for PM, the three comb lines are extremely stable for being free from bias drift problems.

4 Conclusion

We have demonstrated a power efficient ultraflat OFC using two cascaded MZM and PM. The OFC has 15 lines with a flatness of 0.19 dB. Comb spacing is adjustable within the bandwidth of modulators. Moreover, the scheme has very low requirement on the applied RF power and V_π of modulators. In the experiment, commercial modulators are used and a total RF power of 18.3 dBm is applied. It is believed that this high-quality OFC generation scheme with low-power consumption and cost can benefit the application of OFC in microwave photonics and optical communications with limited power supply.

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Biographies for the authors are not available.