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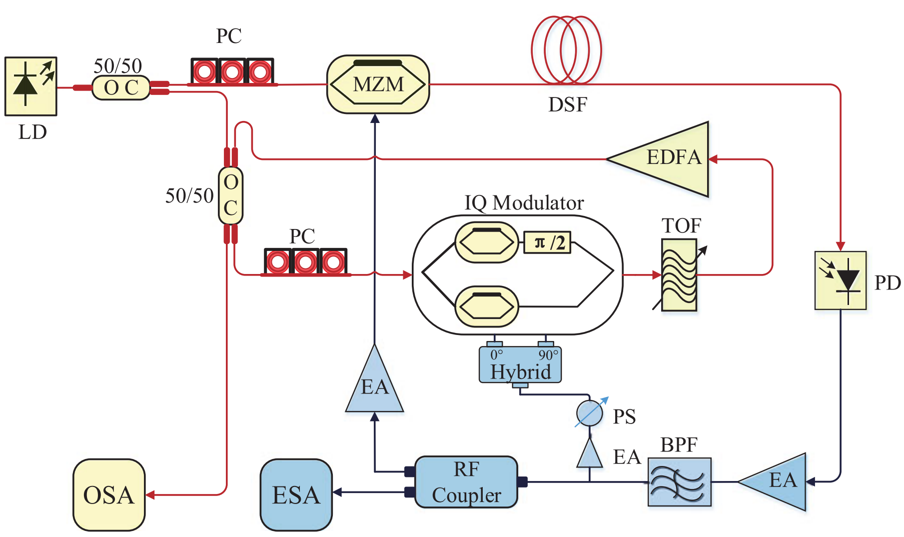

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A Broadband, Rectangular, and Self-Sustained Optical Frequency Comb Generation Employing Recirculation Frequency Shifter

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Abstract: To generate a self-sustained rectangular optical frequency comb (OFC) with tunable spacing and bandwidth, we propose and experimentally demonstrate a novel scheme by using an optoelectronic oscillator employing recirculation frequency shifter (RFS) loop. In this scheme, the oscillating signal is separated to drive the Mach–Zehnder modulator (MZM) in the oscillation loop and the inphase/quadrature modulator in the RFS loop separately. Then more than 50-tone OFCs, which have a rectangular spectral profile and the flatness better than 6 dB, are obtained with 8-GHz spacing and 10-GHz spacing by tuning the center frequency of the microwave filter respectively. Besides, the phase noise of the driving signals are both lower than −110 dBc/Hz at 10 kHz offset frequency.

Index Terms: Recirculation frequency shifting (RFS), optical frequency comb (OFC), inphase/quadrature (I/Q) modulator, optoelectronic oscillator (OEO).

1. Introduction

In recent years, the generation of optical frequency comb (OFC) has drawn a tremendous amount of attention in many fields such as wideband multi-wavelength laser source [1]–[4], radio over fiber system [5], [6], optical arbitrary waveform generation [7], and microwave photonics filters [8]. For the comb lines, the power fluctuation, the line spacing and the total number are key factors in the final applications. A number of alternative approaches have been proposed for the generation of OFC. One typical type of the OFC generation method is the passively mode-locked lasers [9], [10]. The passively mode-locked laser can generate optical frequency combs with a broadband smooth spectral profile, but the repetition rate is usually very low. To enlarge the wavelength spacing, the cascaded electro-optical modulation method has been widely adopted [11]–[15]. However, the number of generated comb lines is usually limited for a given flatness, even the driving signal with high power is fed into the modulators. The OFC can also be produced by four-wave mixing (FWM) in a nonlinear medium [16]. Generally, it is very hard to flatten the OFC lines due to the low

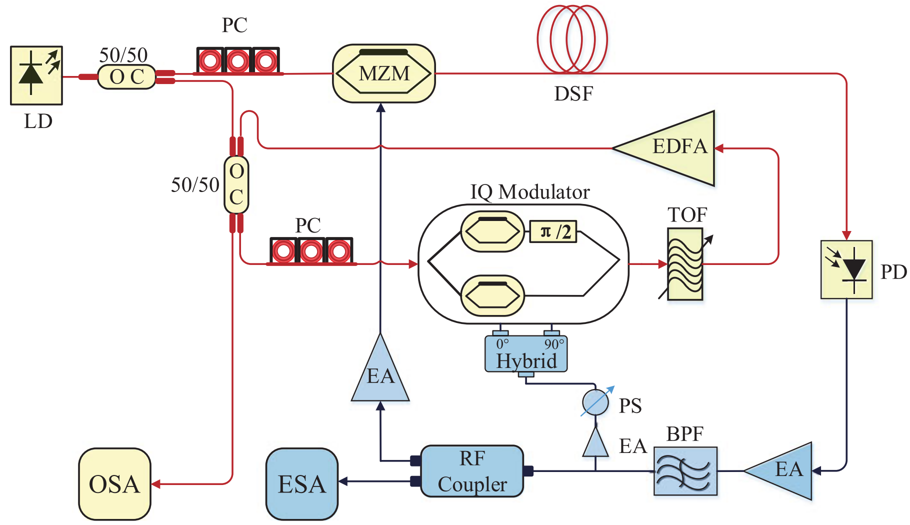

Fig. 1. Schematic configuration of the proposed OFC generator (LD: laser diode; OC: optical coupler; PC: polarization controller; MZM: Mach-Zehnder modulator; DSF:dispersion shifted fiber; EDFA: erbium-doped fiber amplifier; I/Q modulator: inphase/quadrature modulator; TOF: tunable optical filter; OSA: optical spectrum analyzer; PD: photodetector; BPF: bandpass filter; EA: electrical amplifier; PS: phase shifter; ESA: electrical spectrum analyzer).

power efficiency of the FWM. To generate huge-number multi-carriers, the recirculating frequency shifting (RFS) loop [17]–[21] has received considerable attention for its advantages in generating broadband OFC with high flexibility and a flat-top rectangular spectrum. However, a high frequency external RF source with high spectral purity is extremely essential.

In this paper, we propose and experimentally demonstrate a novel scheme on the generation of broadband OFC without any external RF source. A self-sustained OFC with a rectangular spectral profile is produced incorporating the optoelectronic oscillation (OEO) and RFS loops. The frequency comb interval is determined by the oscillation frequency, which is dependent on the passband of the microwave filter in the OEO loop. Since a C-band gain-flattened erbium-doped optical fiber amplifier (EDFA) is used in the RFS loop, there is a flat floor for all the optical spectra. By configuring the tunable optical filter (TOF), we can adjust the number of the comb lines and restrict the comb spectrum with a rectangular spectral profile. In the proof-of-concept experiment, we finally generate a 57-tone OFCs with 8 GHz spacing and a 50-tone OFCs with 10 GHz spacing. The power fluctuation of the self-sustained OFCs is smaller than 6 dB, and the tone-to-noise ratio (TNR) of the OFCs with 8 GHz and 10 GHz spacing is about 14 dB and 20 dB, respectively. Additionally, the performance of the relevant OEO is also evaluated, and the measured phase noise are both lower than −110 dBc/Hz at 10 kHz offset frequency.

2. Principle

The schematic diagram of the proposed self-sustained optical frequency comb generator is shown in Fig. 1. The whole system mainly consists of two parts: the optoelectronic oscillation loop and the recirculating frequency shifting loop. In the oscillation loop, the light from the distributed feedback laser (DFB) is fed into the MZM, and a polarization controller (PC) is installed before the MZM to achieve the maximum modulation efficiency. Then the dispersion shifted fiber (DSF) is used to realize the energy storage function and reduce the phase noise of the oscillation signal. Finally, the photodetector converts the light wave into a feedback electrical signal. In the electrical feedback chain, the microwave bandpass filter and amplifiers are employed to select the final oscillation mode and compensate the link loss. After the first stage amplifier, fifty percent of the RF power

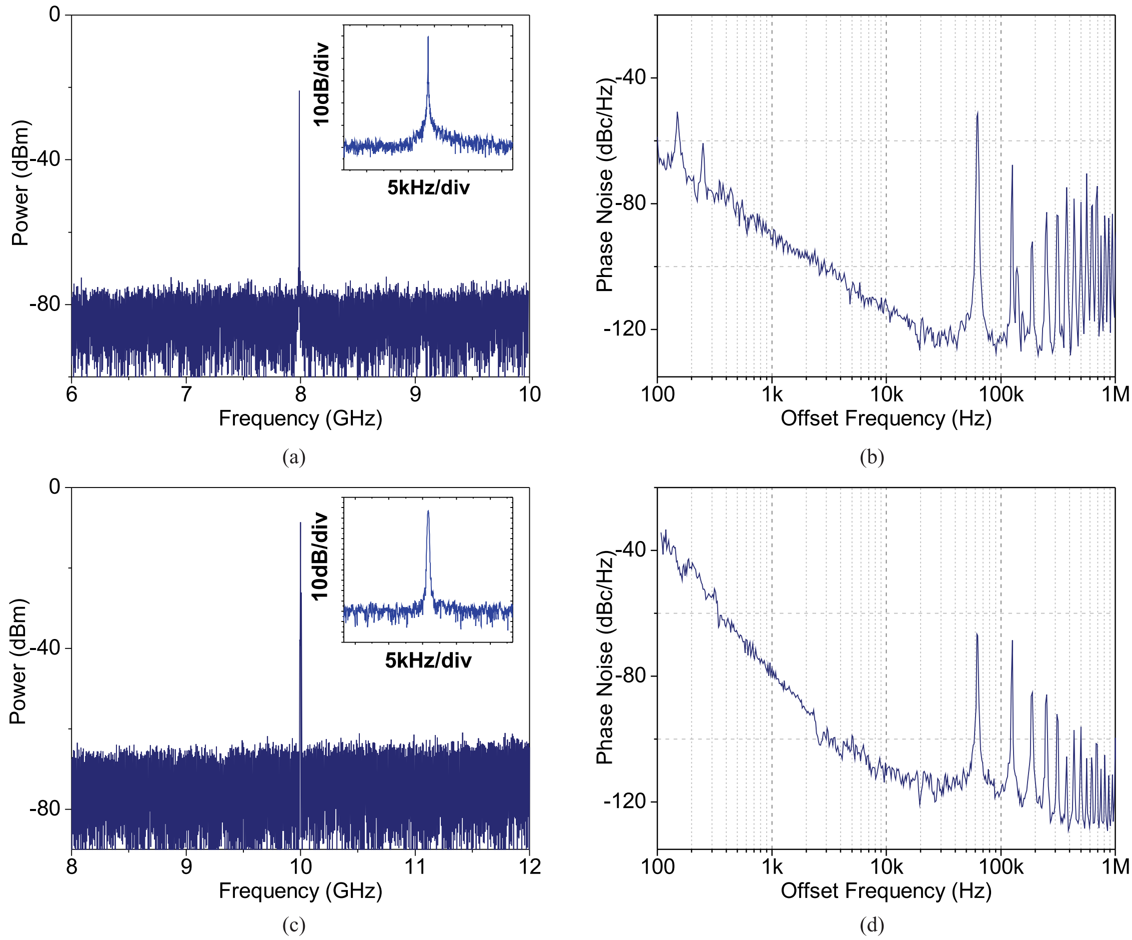

Fig. 2. (a) Electrical spectrum of the 8 GHz microwave signal. The inset gives a zoom-in view of the 8 GHz signal with a frequency span of 50 KHz. (b) Phase noise of the generated 8 GHz microwave signal. (c) Electrical spectrum of the 10 GHz microwave signal. The inset gives a zoom-in view of the 10 GHz signal with a frequency span of 50 KHz. (b) Phase noise of the generated 10 GHz microwave signal.

is separated to the RFS loop, and the rest is sent back to the MZM to form the optoelectronic oscillation loop.

In the RFS loop, an I/Q modulator driven by the oscillation signal is used to realize the single sideband frequency shifting, and the PC before the I/Q modulator is used to fit the shape of the OFC by optimizing the modulation efficiency. Every time the circulating optical signal passes through the I/Q modulator, the optical carrier would be frequency shifted according to the oscillating frequency, and the input continuous wave (CW) laser source will occupy the blank position. As a result, there will be one new frequency component appearing after each circle. The EDFA and the tunable band pass optical filter are used to compensate the transmission loss and confine the spectra range respectively, which can help to generate the broadband and rectangular OFC.

As the key component of the RFS system, the I/Q modulator consists of parallel MZMs in two arms and a phase modulator in one arm. By settling a hybrid before the I/Q modulator, the RF signal from the oscillation loop is divided into two parts with equal amplitudes and $\pi/2$ phase shift difference. Assuming that the injected CW light is represented as $E_{in}(t) = E_0 \exp(j2\pi f_0 t)$, and the RF driving signals on two arms with a fixed phase difference of $+\pi/2$ or $-\pi/2$ can be represented as $V_I(t) = V_e \sin(2\pi f_s t)$ and $V_Q(t) = V_e \cos(2\pi f_s t)$ respectively. The output optical signal after the carrier suppressed single sideband modulation can be given by [22]

$$E_{out}(t) = \frac{E_{in}(t)}{2}\left[j\sin\left(\frac{\pi}{2}\frac{V_I(t)}{V_\pi}\right) + \sin\left(\frac{\pi}{2}\frac{V_Q(t)}{V_\pi}\right)\right] \quad (1)$$

When using the Jacobi-Anger expansion, (1) can be expressed as

$$\begin{aligned} E_{out}(t) &= \frac{E_{in}(t)}{2}\left[j\sin\left(\frac{\pi V_e}{2V_\pi}\sin(2\pi f_s t)\right) + \sin\left(\frac{\pi V_e}{2V_\pi}\cos(2\pi f_s t)\right)\right] \\ &= E_{in}(t)\cdot j\sum_{k=1}^{\infty} J_{2k-1}(\delta_m)\sin[2\pi(2k-1)f_s t] + E_{in}(t)\cdot\sum_{k=1}^{\infty} j^{2k-2} J_{2k-1}(\delta_m)\cos[2\pi(2k-1)f_s t] \\ &= E_{in}(t)\cdot[J_1(\delta_m)e^{j2\pi f_s t} - J_3(\delta_m)e^{-j6\pi f_s t}] + E_{in}(t)\cdot[J_5(\delta_m)e^{j10\pi f_s t} - \cdots] \end{aligned} \quad (2)$$

where $\delta_m = (\pi V_e)/(2V_\pi)$ denotes the modulation depth, $J_{2k-1}(\delta_m)$ are the first kind odd-order Bessel functions. In our discussion, the dominant harmonic is the third order harmonic, and it will affect the output of the RFS loop. In order to eliminate the crosstalk, we must adjust the driving voltage to satisfy $|-J_3/J_1| \ll 1$. Besides, the power loss introduced in each circle can be compensated by the optical amplifier to flatten the generated OFCs. The optical amplification gain should satisfy $G_R = 1/(J_1)^2$. Then we can get the equal power level between the input seed light and the frequency shift light. While the phase shift per round trip is ϕ_T, the output signal after first circle can be describe as

$$E_1(t) = E_{in}(t) + \sqrt{G_R}E_{in}(t)\cdot J_1(\delta_m)e^{j2\pi f_s t}\cdot e^{j\phi_T} = E_{in}(t)(1+K) \quad (3)$$

where $K = e^{j2\pi f_s t + j\phi_T}$ means the frequency shifting of f_s and K^n means the shifting of $n\cdot f_s$.

Assuming that the loop loss can be compensated exactly by the optical amplifier, the outputs after passing $n(n = 1, 2, \ldots, N)$ rounds can be obtained from (3)

$$\begin{aligned} E_1(t) &= E_{in}(t) + E_{in}(t)\cdot K = E_{in}(t)\cdot(1+K) \\ E_2(t) &= E_{in}(t) + E_1(t)\cdot K = E_{in}(t)\cdot(1+K+K^2) \\ &\cdots \\ E_N(t) &= E_{in}(t) + E_{N-1}(t)\cdot K = E_{in}(t)\cdot(1+K+K^2+\cdots+K^N) \\ &= E_{in}(t)\cdot\sum_{n=0}^{N} K^n \end{aligned} \quad (4)$$

Therefore, the final flat and rectangular OFC can be generated. The interval and number of the OFCs will be determined by the oscillating frequency of the OEO and the pass-band bandwidth of the optical filter.

3. Experiments and Results

The proposed broadband and self-sustained OFC generator has been theoretically analyzed above. In order to demonstrate its feasibility, an experiment based on the setup shown in Fig. 1 has been performed. In our experiment, the DFB laser (EM650 high power DFB laser module with a linewidth of 170 kHz) with the wavelength set at 1550 nm is injected into the MZM (EOspace and with a half-wave voltage of 4 V) in the OEO loop and the I/Q modulator (Fujitsu and with a half-wave voltage of 2.8 V) in the RFS loop respectively. Before the MZM and the I/Q modulator, the PCs are used to align the polarization state of the input light with the main axis of the modulators. In the oscillation loop, 3 km DSF is inserted to improve the Q factor of the oscillation loop. The optical-to-microwave conversion is achieved by a high-speed PD (0.5 A/W responsivity and 40 GHz bandwidth). In order to compensate the gain loss from the optical link, the RF amplifiers are employed in the electrical feedback path. Moreover, oscillation frequency selection is realized by a bandpass filter with the

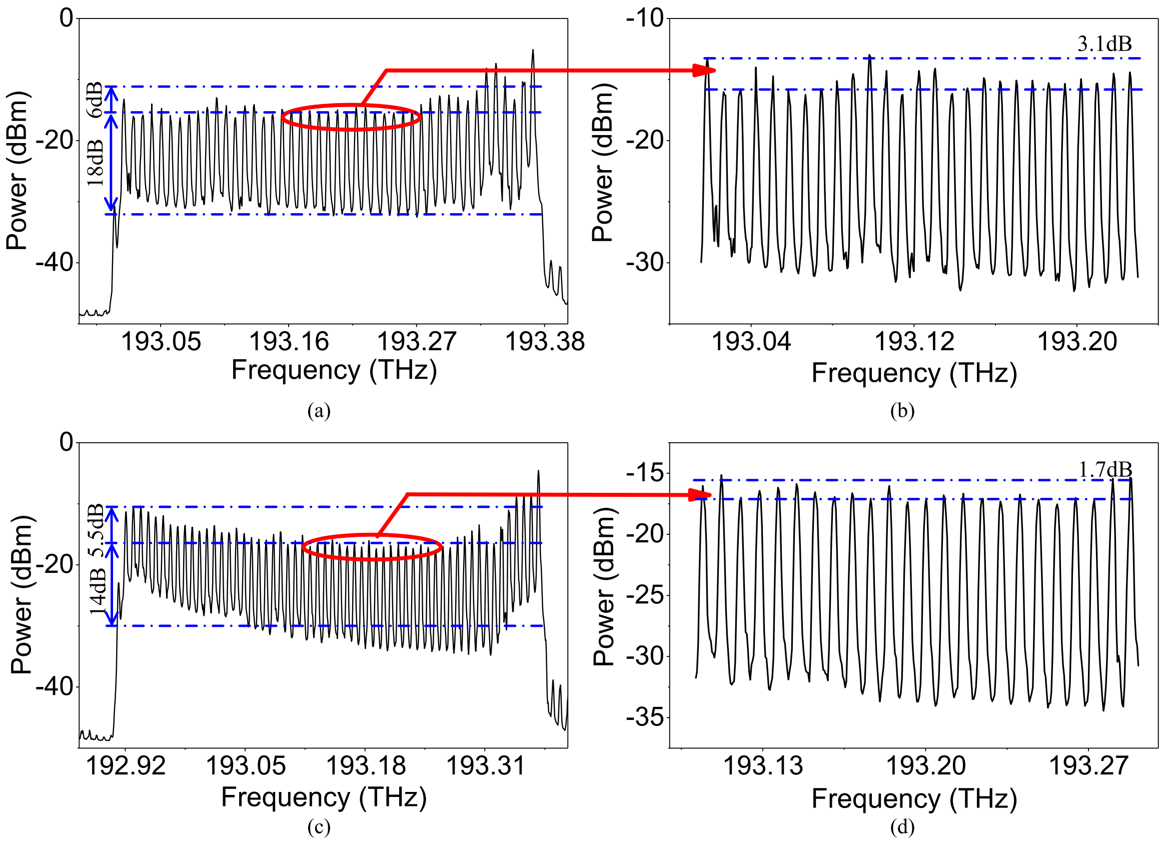

Fig. 3. Spectrum of an optical frequency comb (a) a 46-tone OFC with 8-GHz spacing, (b) a 57-tone OFC with 8-GHz spacing, (c) subcarriers from 193.015 THz to 193.229 THz, (d) subcarriers from 193.101 THz to 193.292 THz.

center frequency set at 8 GHz and 10 GHz respectively. Then the filtered signal is divided into two paths by a 3 dB power divider, and half power returns to the oscillation loop while the rest is sent to the RFS loop to build up the OFC generator. In addition, the insertion loss of the phase shifter and the hybrid is close to 3 dB which will ensure the different modulation depth of the two loops with the same electrical amplifiers. In the RFS loop, a TOF (Finisar) is used to adjust the number and optimize the shape of the comb lines. After the TOF, an EDFA (Keopsys) with 25 dBm output power is used to compensate the loss in the closed loop.

In Fig. 2, it illustrates the oscillation signals separated from the RF filter with different center frequencies. Besides, the measured electrical spectra of the generated RF signals at 7.98 GHz and 10 GHz are shown in Fig. 2(a) and (b), where the insets show the zoom-in view in a span of 50 kHz. The phase noise performance of the 7.98 GHz and the 10 GHz RF signals from 100 Hz to 10 MHz offset frequency is shown in Fig. 2(c) and (d). It displays that the phase noise of the 7.98 GHz and 10 GHz signals at 10 kHz offset frequency is as low as −112 dBc/Hz and −111.5 dBc/Hz, respectively.

For the OFC generation, an 8 GHz BPF is firstly employed, and then the passband bandwidth of the TOF is tuned at 350 GHz and 460 GHz respectively. Finally the broadband OFC with a rectangular spectrum is obtained in the experiment. Fig. 3(a) and (c) illustrate the 46-tone and 57-tone OFCs with peak-to-peak power fluctuation less than 6 dB and TNR higher than 14 dB. The power fluctuation is caused by the nonflatness of the EDFA gain spectrum. In the scheme, the tone whose frequency is further away from the seed light frequency experiences more turns in the RFS loop. For each circulation, the comb line obtains gain from the EDFA, and additional

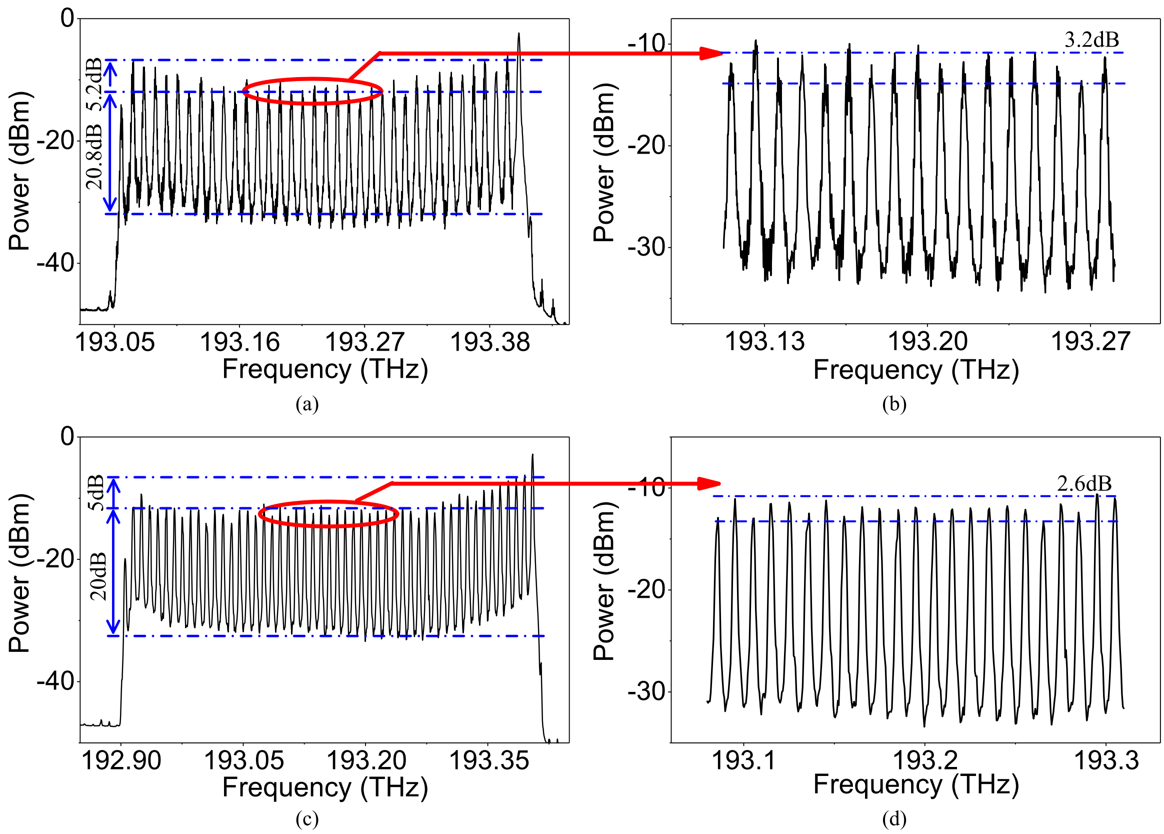

Fig. 4. Spectrum of an optical frequency comb (a) a 35-tone OFC with 10-GHz spacing, (b) a 50-tone OFC with 10-GHz spacing, (c) subcarriers from 193.113 THz to 193.280 THz, (d) subcarriers from 193.079 THz to 193.309 THz.

noise is also imposed to the frequency shifting light which causes the climbing of the noise floor. In addition, Fig. 3(b) and (d) illustrate the detailed optical spectra of subcarriers from Fig. 3(a) and (c). Particularly, the 8-GHz-spacing subcarriers are with good shape and flatness, and the TNR is larger than 20 dB at the selected range.

By changing the center frequency of the BPF at 10 GHz and configuring the bandwidth of the TOF at 350 GHz and 500 GHz, respectively, the 10-GHz-spacing OFC can be obtained with the optical spectra illustrated in Fig. 4. The rectangular OFCs with 35-tone and 50-tone are shown in Fig. 4(a) and (c). The peak-to-peak power fluctuation of the generated OFCs is less than 5 dB, and the TNR is higher than 20 dB. In Fig. 4(b) and (d), the detailed optical spectra show that the subcarriers have rectangular shape and high TNR.

4. Conclusion

In conclusion, we propose and experimentally demonstrate a novel scheme incorporating the optoelectronic oscillation and recirculating frequency shift loops to generate self-sustained optical frequency comb with a rectangular spectral profile. In this scheme, the broadband OFC can be generated without any extern RF source, and the line spacing of the OFC would be tuned by changing the center frequency of the BPF in the oscillation loop. The experimentally generated 8 GHz and 10 GHz spacing OFCs have more than 50 comb lines with the flatness better than 6 dB and TNR higher than 14 dB and 20 dB, respectively. Besides, the phase noise of the RF driving signals are both lower than −110 dBc/Hz at 10 kHz offset frequency.

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