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Flat optical frequency comb generation and its application for optical waveform generation

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A B S T R A C T

We demonstrate the generation of a flat optical frequency comb (OFC) using an electro absorption modulator (EAM) and two cascaded phase modulators (PM). Compared with previous flat OFC generation schemes using a Mach–Zehnder modulator (MZM) for amplitude gating of the phase modulated light, an EAM creates much shorter time window for amplitude gating, and more flattened OFC spectrum is obtained using EAM as an amplitude gate. In our experiment, a very flat OFC having 11 lines within 3-dB bandwidth (3.8 nm), and 40 GHz comb line spacing is generated. Besides the excellent spectral flatness, the strong time-domain linear-chirp of the generated OFC can be simply compensated by a dispersion compensation fiber (DCF) link, which is preferred for optical waveform generation based on spectral manipulation. In this paper, we also demonstrate the OFC application for generation of several optical waveforms by manipulating the amplitude and phase of the comb lines. High repetition-rate optical cosine pulse, optical pulse burst, optical square and triangle pulses are successfully generated.

1. Introduction

Optical frequency comb (OFC) generation has attracted much attention, because of its widespread applications, such as dense-wavelength-division multiplexing (DWDM), optical orthogonal-frequency-division multiplexing (O-OFDM), short optical pulse generation, and arbitrary waveform generation, etc. [1–3]. Many schemes have been proposed for OFC generation. In general, these schemes can be divided into three categories: using mode locked lasers [4,5], using nonlinear effects in a nonlinear medium [6,7], and using modulation methods by electro-optical modulators (EOM) [8–14]. The OFC generation based on EOM is thought to be the most promising technique, which has advantages such as low complexity, high stability, as well as the ease of frequency-tunability. One of the commonly used methods for OFC generation based on EOM is phase modulation of a continuous wave (CW) light. By increasing the modulation depth, the bandwidth of generated optical spectrum can be broadened and wide-range OFC is obtained. To further enlarge the OFC bandwidth, intra-cavity scheme where electro-optical phase modulators (PM) are set inside a loop structure can be adopted [13,14]. Compared to single-path structure, intra-cavity schemes can achieve wider-range OFC spectrum but have more complicated structure, because the cavity length needs to be accurately tuned and optical amplifiers or pumps are usually required to compensate the optical power loss. A common problem of such phase modulation methods for OFC generation is that, with the PM driven by sinusoidal radio-frequency (RF) signals, it is hard to obtain flattened spectrum [10]. However, for optimum performance in many applications such as RF photonic filtering [1], excellent spectral flatness is preferred. A simple method to get flattened OFC is to reshape the phase modulated spectrum using certain optical filtering system [13], but the quality of the OFC is usually degraded. For example, the optical signal-to-noise-ratio (OSNR) will get worse because the comb lines with large power amplitudes are cut to the same height with the shortest comb line. On the other hand, several approaches that directly generate flat OFC have been reported, among which the most practical method is to gate the amplitude of the phase modulated CW light [10]. In many previous works, Mach–Zehnder modulators (MZM) are used for amplitude gating [10,11], and the obtained OFC spectrum is flattened compared with the phase modulation configuration. Since a narrower time-domain amplitude gating helps to obtain more flattened optical spectrum [10], the flatness of the OFC can be improved by shrinking the time window of the amplitude gate. In this paper, we demonstrate the generation of a flat OFC using an electro absorption modulator (EAM) and two cascaded phase modulators (PM), where EAM plays the role of an amplitude gate which has much shorter time window than that created by an MZM. By comparing the properties of the OFC generated using EAM and

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MZM for amplitude gating, respectively, it is confirmed that more flattened OFC is generated using EAM for amplitude gating.

Another feature of the OFC generated using EAM for amplitude gating is that it has a strong quadratic phase modulation character in time domain. After linear-chirp compensation with just a dispersion compensation fiber (DCF) link, the optical comb is highly preferred in line by line pulse shaping for optical arbitrary waveform generation (OAWG) [15], because the amplitude and phase of the comb lines need to be specially designed and any residual phase modulation upon the OFC will affect the OAWG performance. In this paper, we also demonstrate several optical waveforms generation based on the generated OFC, by manipulating the amplitude and phase of the comb lines. High repetition-rate optical cosine pulse, optical pulse burst, optical square and triangle pulses are successfully generated.

2. Principle of flat OFC generation

Phase modulation of a CW light source leads to the generation of many sidebands in the optical spectrum, which can be used for OFC generation [10]. By increasing the phase modulation depth, more spectral sidebands can be generated, and a wide-range OFC is obtained. The main problem of this method is poor spectral flatness, because the phase modulators are usually driven by sinusoidal RF signals. Fig. 1 shows the sinusoidal phase modulation and the correspondingly induced instantaneous frequency, i.e., the derivative of the sinusoidal phase with respect to time. As shown in Fig. 1, the instantaneous frequency caused by sinusoidal phase modulation has the same value at two different times within a modulation period (25 ps in Fig. 1), resulting in spectral interference which causes variation in the power spectrum [15]. To avoid the spectral interference, one method is to implement quadratic phase modulation, which induces linear instantaneous

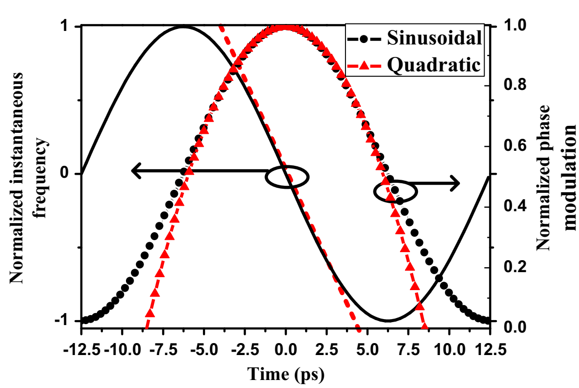

Fig. 1. The sinusoidal (black) and quadratic (red) phase modulation and the correspondingly imposed sinusoidal and linear instantaneous frequency. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

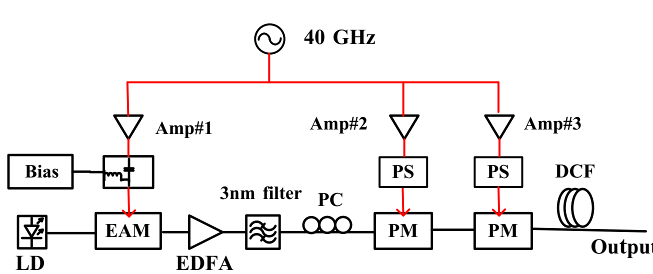

Fig. 2. Setup of our proposed frequency comb generation scheme.

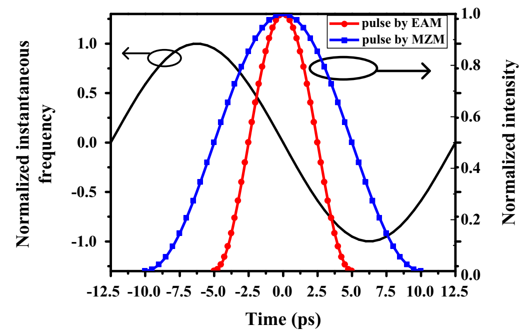

Fig. 3. Normalized intensity profile of optical pulses generated by EAM and MZM, and the instantaneous frequency induced by sinusoidal phase modulation.

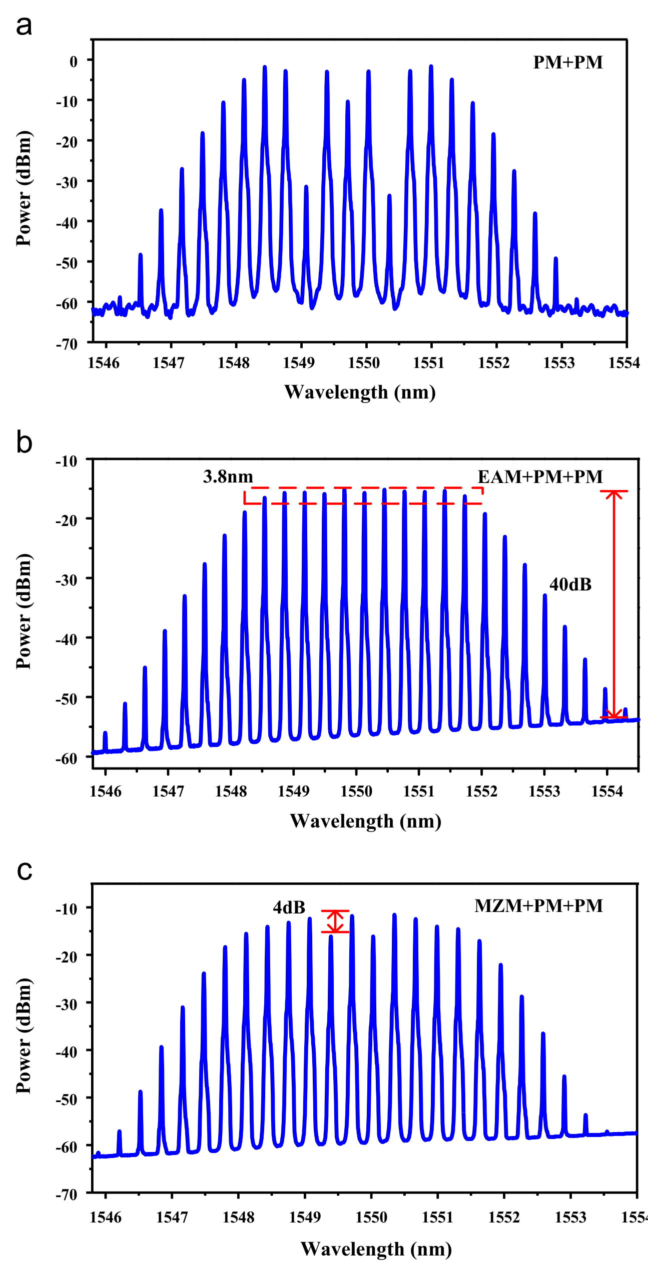

Fig. 4. (a) Optical spectrum when only two PMs are used. (b) Spectrum of generated OFC using EAM and two PMs. (c) Spectrum of generated OFC using MZM and two PMs.

frequency. For ease of understanding, the quadratic phase modulation and the linear instantaneous frequency caused by quadratic phase modulation are also shown in Fig. 1. This method is theoretically proved feasible [16] but not practical because it is hard to achieve high repetition-rate quadratic RF signals, and all optical method based on cross phase modulation in a nonlinear medium [17] is very complicated to realize. A practical method to avoid the spectral interference and generate flat OFC is gating the amplitude of a sinusoidal phase modulated CW light into less than half of the modulation period, thus a particular instantaneous frequency appears only once within a modulation period. It has been demonstrated that using an MZM for time-domain amplitude gating, the flatness of the frequency comb is improved. For intensity modulation, the transfer function of MZM is a raised cosine function given as [18]

$$T_{MZM}(V) = \frac{1}{2}\left[1 + b\cos\left(\pi\frac{V}{V_\pi} + \Phi_0\right)\right] \tag{1}$$

where V is the applied voltage; b is an imbalance factor between the arms of the MZM; Φ_0 is the phase difference of the two MZM arms at zero applied voltage; V_π is the half-wave voltage. Usually, the obtained optical pulse after amplitude gating by an MZM still covers a time-duration more than half of the modulation period (which can be proved in the next part), thus there is still room for improvement of the flatness by further shirking the time window of the amplitude gate. Also according to [18], the transfer function of an EAM is

$$T_{EAM}(V) = t_0 e^{-\gamma\alpha(V)L} \tag{2}$$

where t_0 is the insertion loss of the EAM at zero applied voltage; γ is the optical confinement factor; $\alpha(V)$ is the change of optical absorption coefficient due to the applied voltage V; L is the modulation length. By properly setting the EAM bias voltage and amplitude of the RF driving signal, much shorter optical pulse can be generated by an EAM, and more flattened OFC can be generated.

3. Experimental demonstration of flat OFC generation

Fig. 2 shows the experimental setup of the OFC generation scheme. A CW light from a laser diode (LD) at 1549.5 nm with the power of 7 dBm is modulated by a 40 GHz EAM (CIP 40G-PS-EAM-1550-OP1) which is inverse-biased and driven by a 40 GHz sinusoidal RF signal. At the output of the EAM, a 40 GHz repetition-rate optical pulse train is generated. After EAM, an erbium doped fiber amplifier (EDFA) is used to compensate the loss. A 3-nm optical filter is followed to suppress the amplified spontaneous emission (ASE) noise. Then, the optical pulse train is modulated by two cascaded PMs, of which the V_π values are both 10 V at 40 GHz. The 40 GHz RF signals driving the PMs are properly delayed by electrical phase shifters (PS) for synchronization. In order to sufficiently broaden the optical spectrum by phase modulation, we set the amplitude of the PM driving signals as large as possible. After properly setting the EAM bias voltage and the amplitude of its driving RF signal, the full-width at half-maximum (FWHM) of the generated 40 GHz optical pulse can be tuned to as short as 5 ps, and this value for pulses generated using a 40 GHz MZM is typically around 10 ps. Fig. 3 shows the normalized intensity profile of the optical pulses generated by an EAM and an MZM (Fujitsu FTM7938EZ), where the phase modulation induced sinusoidal instantaneous frequency is also

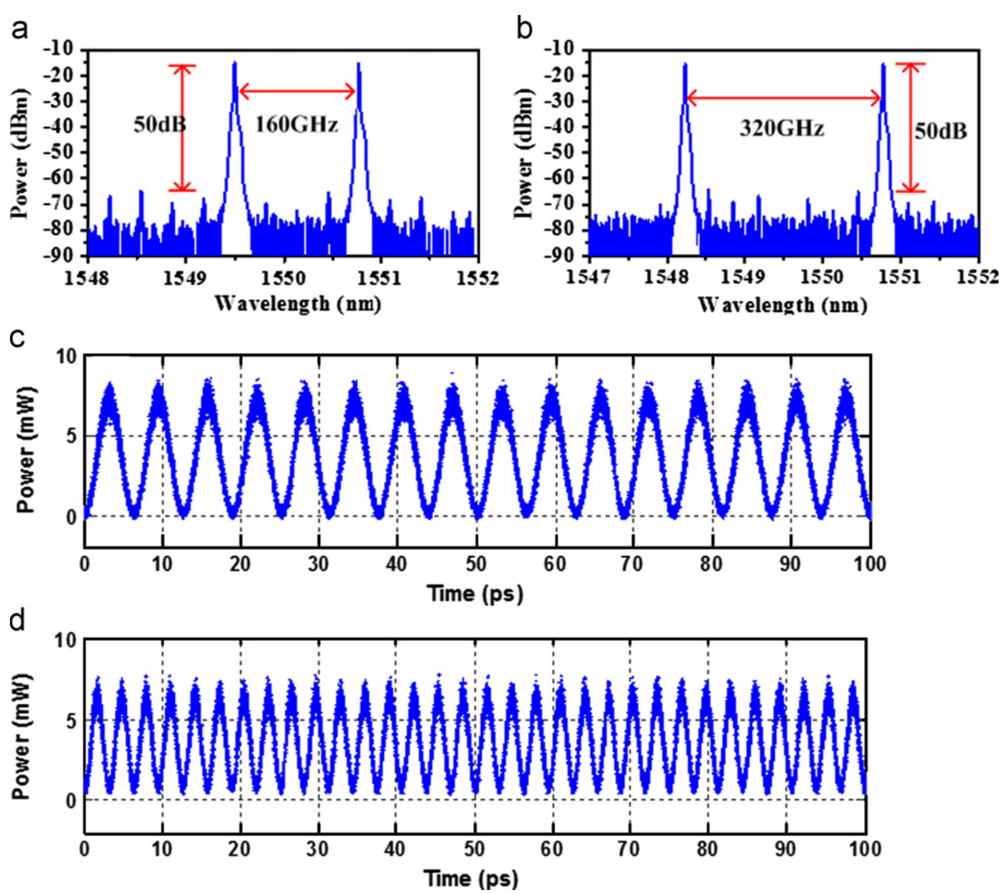

Fig. 5. (a) Spectrum of selected two comb lines with 160 GHz spacing. (b) 160 GHz optical sinusoidal waveform. (c) Spectrum of selected two comb lines with 320 GHz spacing. (d) 320 GHz optical sinusoidal waveform.

included. In Fig. 3, the optical pulse obtained by EAM is obviously much better confined to half of the modulation period (12.5 ps) than the pulse obtained by the MZM. This means that, using EAM for amplitude gating can avoid the spectral interference more completely than the scheme using MZM, and a more flattened optical frequency comb can be generated.

Fig. 4(a) shows the measured optical spectrum when only two PMs are used for comb generation. As explained above, the spectrum in Fig. 4(a) has poor flatness, and large amplitude variation can be observed. When EAM is used for amplitude gating, the obtained OFC spectrum is obviously flattened, as shown in Fig. 4(b), where the OFC has 40 GHz comb line spacing and 11 comb lines within 3-dB bandwidth (3.8 nm). The optical signal-to-noise ratio (OSNR) obtained from the spectrum is as high as 40 dB. For comparison, we also measure the OFC spectrum obtained using an MZM as the amplitude gate, i.e., when the EAM is replaced by a 40 GHz MZM in Fig. 2, as shown in Fig. 4(c). The OFC spectrum in Fig. 4(c) has improved flatness compared with that in Fig. 4(a), but there are still obvious fluctuations in the power spectrum. A power variation of about 4 dB is observed near the carrier wavelength in Fig. 4(c), and this power variation in Fig. 4(b) is about 0.9 dB, which confirms the better flatness of the OFC spectrum generated using EAM for amplitude gating compared to the OFC generation using MZM for amplitude gating. Another issue is the OFC bandwidth or the comb line numbers in the flat region. It is found that, the OFC bandwidth is mainly determined by the phase modulation depth of the two PMs. The results in Fig. 4 correspond to the largest OFC bandwidth we can obtain using our experimental devices. When reducing the amplitude of the PM driving signals, or simply using one PM, the obtained OFC bandwidth is accordingly reduced. To enlarge the OFC bandwidth, larger amplitude PM driving signals or PM with larger modulation index can be applied.

4. Optical waveform generation

Through Fig. 3, it is observed that the OFC generated using EAM for amplitude gating has a strong quadratic phase modulation or linear-chirp character in time-domain. Simply using a span of DCF with proper length after the cascaded PMs (see Fig. 2), the linear-chirp can be compensated. Based on this time-domain chirp-free OFC, we demonstrate its application for OAWG by means of spectral line manipulation, which is done using a programmable optical processor (Finisar-Waveshaper-4000S). The optical processor can manipulate both the amplitude and phase of the input spectrum with 1 GHz resolution, and the out-of-band intensity suppression ratio can be as high as 50 dB.

First, we implement the generation of high repetition-rate optical cosine pulse. By selecting out two of the frequency comb lines, the optical intensity waveform becomes a cosine function with the frequency equals to the spacing between the two selected spectral lines. Optical cosine pulses with repetition-rate of 40 GHz, 80 GHz, and 120 GHz … (integral multiple of comb line spacing) can be generated. As two examples, the optical spectra after selecting two comb lines with 160 GHz and 320 GHz spacing are shown in Fig. 5(a) and (b), respectively. The corresponding time-domain waveforms are observed through a 500 GHz optical sampling oscilloscope (OSC) (EXFO-PSO-102), as shown in Fig. 5(c) and (d), respectively. In Fig. 5(c) and (d), the optical cosine pulse trains with 160 GHz and 320 GHz repetition-rates are successfully generated.

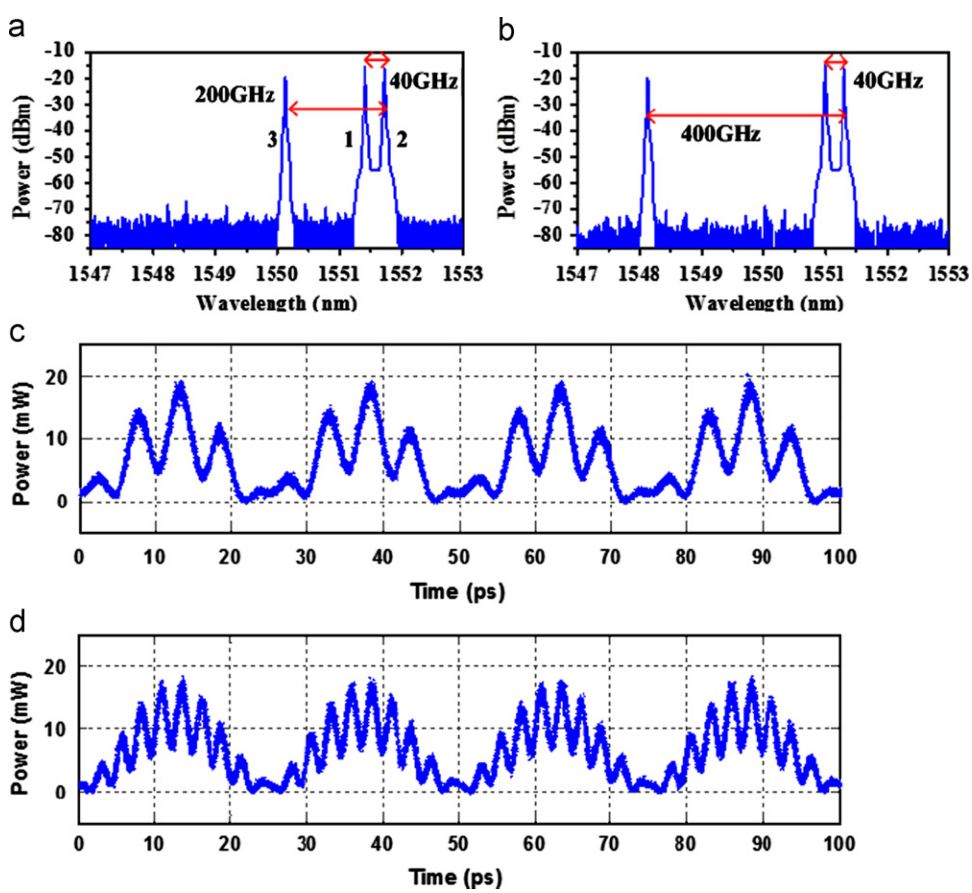

Fig. 6. (a) Optical spectrum for selected three comb lines with 180 GHz separation between the third line and the center of the first two lines. (b) The generated pulse burst with macro period of 25 ps and micro period of 5.56 ps. (c) Optical spectrum for selected three comb lines with 380 GHz separation between the third line and the center of the first two lines. (d) The generated pulse burst with macro period of 25 ps and micro period of 2.63 ps.

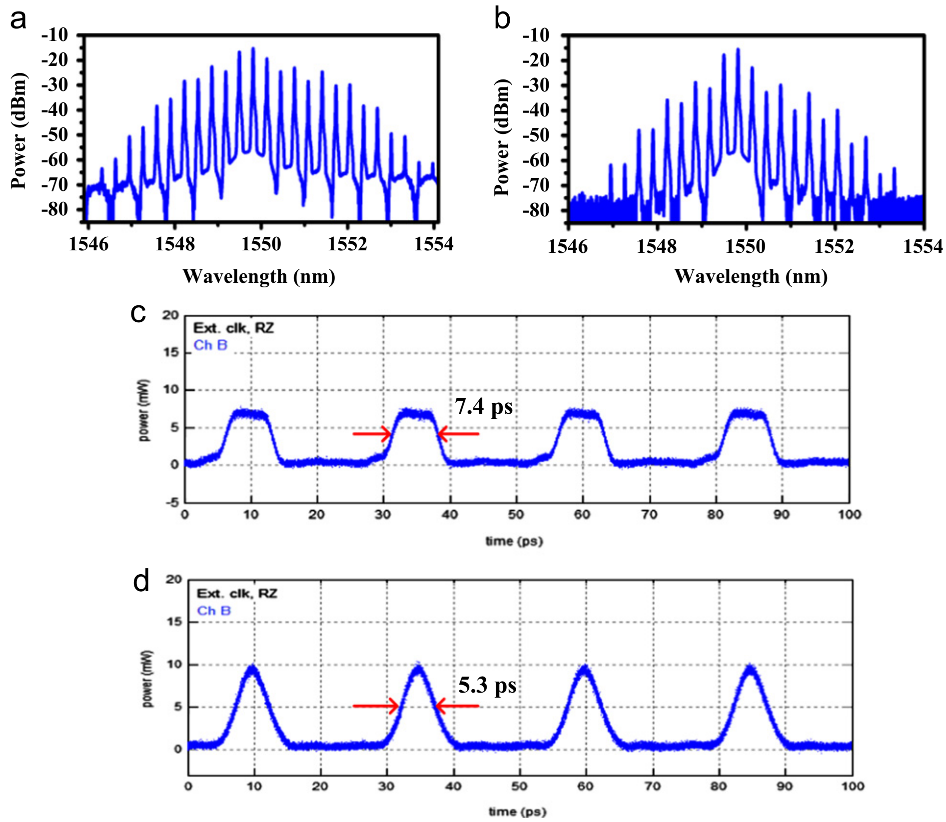

Fig. 7. (a) The Optical power spectrum after Sinc function filter. (b) The temporal waveform of generated 40 GHz square pulse train. (c) Optical power spectrum after Sinc^2 function filter. (d) The temporal waveform of generated 40 GHz triangle pulse train.

Optical pulse burst can be generated by properly selecting out three comb lines, as shown in Fig. 6. In Fig. 6(a), two of the comb lines (line 1 and 2) are selected with 40 GHz frequency separation and the third comb line (line 3) is 200 GHz apart from line 2. The correspondingly generated optical pulse burst in Fig. 6(c) has an envelop of sinusoidal function with the period of 25 ps, which is determined by the 40 GHz spacing between the first two spectral lines. The duration of each small pulse in Fig. 6(c) is 5.56 ps, corresponding to the 180 GHz separation between the third spectral line and the center of the first two spectral lines. Fig. 6(b) shows the optical spectrum when the third spectral line is 380 GHz apart from the center of the first two spectral lines. The obtained optical pulse burst in Fig. 6(d) has macro period of 25 ps (corresponding to 40 GHz separation) and micro period of 2.63 ps (corresponding to 380 GHz separation).

Optical square pulse and triangle pulse can be generated by passing the OFC through a sinc function filter and a sinc^2 function filter, respectively, which is achieved by frequency to time domain conversion based on Fourier transformation [15]. The sinc and sinc^2 filters realized by the optical processor can change both the amplitude and the phase of the input optical spectrum according to their transfer functions. The obtained optical power spectra after the OFC passes through the sinc and sinc^2 filters are shown in Fig. 7(a) and (b), respectively, where the 3-dB bandwidths are both 120 GHz. The correspondingly generated square and triangle pulse trains in time-domain are shown in Fig. 7(c) and (d), respectively. The square pulse width is measured to be 7.4 ps and the FWHM of the triangle pulse is 5.3 ps. For both the square and the triangle pulses, the relation of measured pulse width and the spectral bandwidth complies well with the Fourier transform theory. This confirms that the OFC after DCF has good chirp-free character in time-domain. By changing the sinc or sinc^2 filter bandwidth, the pulse width of generated square or triangle pulse can be changed accordingly.

5. Conclusions

We have experimentally demonstrated the generation of a flat OFC using an EAM and two cascaded PMs, as well as its application for optical waveform generation. The use of EAM for amplitude gating of the phase modulated light with very narrow time window leads to a very flat OFC generation. By comparing the frequency combs obtained by our schemes using EAM and the scheme using an MZM for amplitude gating, better flatness of the frequency comb obtained using EAM is confirmed. By simply using a span of DCF, the linear-chirp of the OFC can be compensated. Based on this time-domain chirp-free OFC, optical waveform generation is realized by spectral manipulation of the comb lines. High repetition-rate optical cosine pulse, optical pulse burst, optical square and triangle pulses are successfully generated.

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