Flat-top optical frequency comb generation based on optical fiber-loop modulation with external injection

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An optical frequency comb generation scheme using time-to-frequency conversion and optical fiber-loop modulation is proposed and demonstrated experimentally. Flat-top optical pulse train from an intensity modulator is injected into a fiber loop, which includes a phase modulator and an amplifier and is cyclically modulated by the phase modulator, to generate abundant optical comb lines. A total of 110 comb lines with 3-dB spectral power variation and 10-GHz frequency spacing are obtained. The proposed scheme is relatively simple and uses only one intensity modulator and one phase modulator.

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Optical frequency comb (OFC) is indispensable in many applications, such as arbitrary waveform generation[1], wavelength division multiplexing[2], optical code division multiple access[3], optical orthogonal frequency division multiplexing[4], and multi-wavelength pulse generation[5]. Two factors are needed to meet the needs of various applications: spectral power variation, i.e., the flatness of OFC, and the number of OFC comb lines. With frequency spacing adjustability and stability capabilities, OFC generated via intensity or phase modulation of a continuous wave laser (CWL) has attracted much research attention for many years[6−9]. A total of 38 comb lines within 1-dB spectral power deviation are obtained by using intensity modulator (IM) and phase modulator (PM) driven by specially tailored radio frequency waveforms[8], and 25 comb lines with comb flatness within 1 dB are generated by using cascaded polarization modulators[9].

However, the number of comb lines depends on the magnitude of modulation achieved by phase or intensity modulation. More comb lines could be obtained by applying larger amplitude of sinusoidal waveform on the PM if the half-wave voltage of the modulator is fixed. However, sinusoidal waveforms with extremely large amplitude cannot be applied on the PM besides scheme complexity increases when the number of cascaded PM increases. Schemes using optical fiber loop modulation (OFLM) are proposed to mitigate this problem[10−12].

We combine time-to-frequency (TTF) conversion[13,14] and OFLM to obtain flat-top OFCs with more comb lines. The experiment is demonstrated by using one IM and one PM, in which the latter is kept in an optical fiber loop. A total of 110 comb lines with 3-dB spectral power variation are demonstrated experimentally. The proposed scheme has the following advantages: only one IM and one PM are used; sinusoidal waveforms require reasonable amplitude; the proposed scheme does not require a wavelength selective switch, a waveform shaper, or a filter to achieve minimal spectral power variation.

The flat-top OFC generated by TTF conversion requires a flat-top optical pulse and a strong quadratic phase[13,14]. Figure 1(a) shows the proposed scheme. The flat-top optical pulse is achieved by intensity modulating a CWL. However, given that the quadratic phase is difficult to obtain, the cosine signal is used to replace the quadratic signal in the scheme[13] because the latter is similar to the former. Figure 1(b) shows the quadratic curve (red dotted line) and cosine curve (black solid line). The phase shift of the cosine signal applied on the IM and PM can equal zero ($\Delta\varphi = 0$) by adjusting the phase shifter. The output of the PM can be expressed as

$$E_{\text{out}} = E_{\text{i}} \exp(\text{i}\Delta\theta_{\text{p}} \cos \omega_{\text{m}} t), \tag{1}$$

where E_{i} is the output of the IM, i.e., the flat-top optical pulse; $\Delta\theta_{\text{p}}$ represents the phase modulation index; ω_{m} is

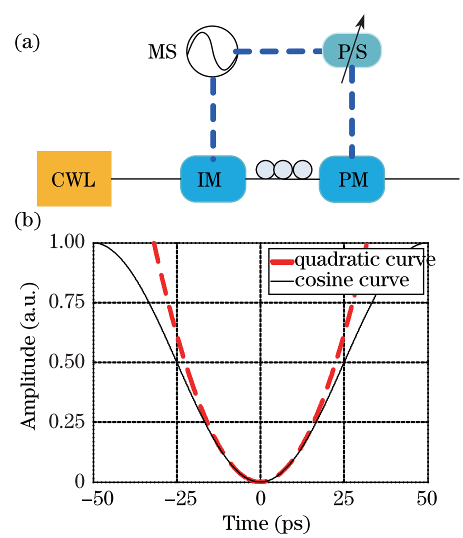

Fig. 1. (Color online) (a) OFC generated by TTF conversion, (b) quadratic curve (red dotted line), and cosine curve (black solid line). MS: microwave source, PC: polarization controller, PS: phase shifter.

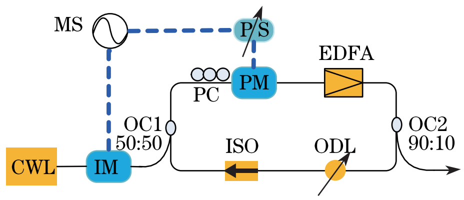

Fig. 2. OFC generation based on TTF conversion and OFLM. OC: optical coupler, ODL: optical fiber delay line, ISO: isolator).

the angular frequency of the cosine signal. The number of comb lines becomes proportional to the phase modulation index $\Delta\theta_{\mathrm{p}}$ when the scheme shown in Fig. 1(a) is used to generate OFC. In this letter, we use TTF conversion and OFLM in generating OFC to obtain a flat-top OFC and to increase the number of comb lines.

Figure 2 shows the scheme that uses TTF conversion and OFLM to achieve flat-top OFC with more comb lines. Optical pulse is injected into the optical fiber loop though a 50:50 optical coupler and is modulated by a PM circularly. The erbium-doped fiber amplifier (EDFA) and isolator are used to compensate the loop loss and to enable the optical pulse to propagate through the optical fiber loop along one direction, respectively. The polarization controller and optical fiber delay line can respectively adjust the polarization state of light in the fiber loop and cavity length for synchronization. The OFC is outputted by a 90:10 optical coupler.

Supposing that the total loss of the fiber loop for one round is $\exp(-\alpha)$, the gain factor of EDFA is g, and the phase delay for each round is θ, then the transfer function of the fiber loop for one round is

$$\begin{aligned} T(t) &= g\exp(-\alpha)\exp(\mathrm{i}\theta)\exp(\mathrm{i}\Delta\theta_{\mathrm{p}}\cos\omega_{\mathrm{m}}t) \\ &= R\exp(\mathrm{i}\theta)\exp(\mathrm{i}\Delta\theta_{\mathrm{p}}\cos\omega_{\mathrm{m}}t), \end{aligned} \tag{2}$$

where $R = g\exp(-\alpha)$ represents the ratio of EDFA gain and the total loss in the fiber loop. By adjusting the optical fiber delay line, we can derive $\theta = 2n\pi$ and $\exp(\mathrm{i}\theta) = 1$. The transfer function of the optical fiber loop for one round is

$$T(t) = R\exp(\mathrm{i}\Delta\theta_{\mathrm{p}}\cos\omega_{\mathrm{m}}t). \tag{3}$$

After fiber loop modulation, the output is

$$\begin{aligned} E_{\mathrm{out\_}N} &= E_{\mathrm{i}}\exp(\mathrm{i}\Delta\theta_{\mathrm{p}}\cos\omega_{\mathrm{m}}t)(1+T+T^2+\cdots+T^N) \\ &= E_{\mathrm{i}}\{\exp(\mathrm{i}\Delta\theta_{\mathrm{p}}\cos\omega_{\mathrm{m}}t)+R\exp(\mathrm{i}2\Delta\theta_{\mathrm{p}}\cos\omega_{\mathrm{m}}t) \\ &+ R^2\exp(\mathrm{i}3\Delta\theta_{\mathrm{p}}\cos\omega_{\mathrm{m}}t) \\ &+ \cdots + R^N\exp[\mathrm{i}(N+1)\Delta\theta_{\mathrm{p}}\cos\omega_{\mathrm{m}}t]\} \\ &= E_{\mathrm{i}}P_l, \end{aligned} \tag{4}$$

where N is the cycle index. Thus, phase modulation is larger when using a fiber loop (P_l) compared with not using a fiber loop [$\exp(\mathrm{i}\Delta\theta_{\mathrm{p}}\cos\omega_{\mathrm{m}}t)$]. If the EDFA can entirely compensate the loss of the fiber loop, then a large number of spectral lines will be generated.

The scheme is demonstrated experimentally. A continuous wave distributed feedback laser, which has an output power of 13 dBm and linewidth of 2 MHz, is used in the experiment. The applied microwave frequency is 10 GHz. The CWL is modulated by the IM and the is modulated by the PM if the OFLM is not used (see Fig. 1). By adjusting the phase shifter and the DC bias, 15 comb lines with 1-dB spectral power variation are obtained (see Fig. 3(b)).

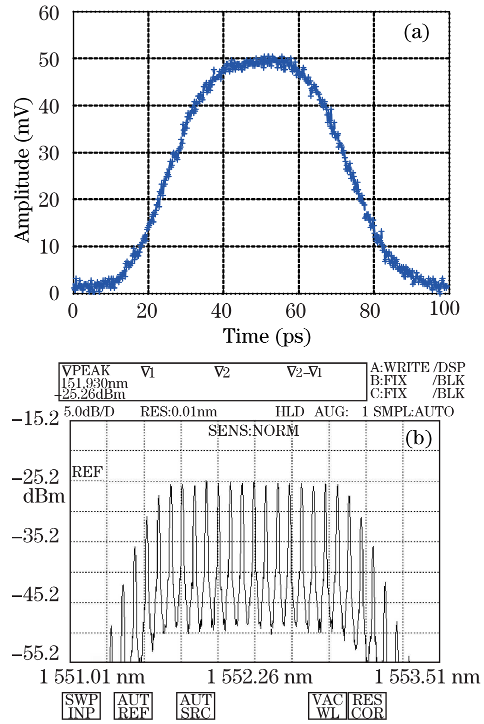

Fig. 3. (a) Optical pulse outputted by an IM. (b) OFC obtained without using OFLM.

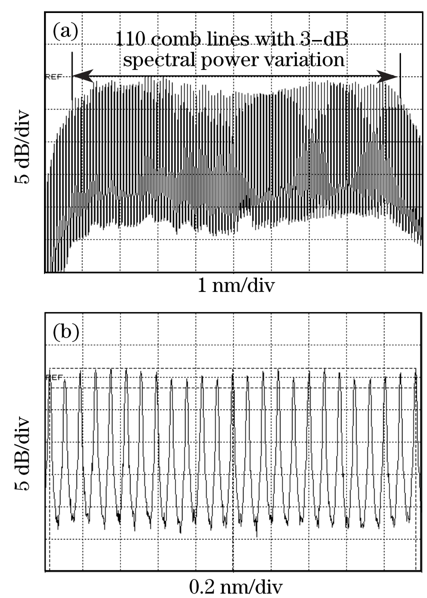

Fig. 4. (a) OFC with 110 comb lines obtained from OFLM. (b) detailed drawing of (a).

When the optical pulse is injected into the optical fiber loop, the optical pulse is modulated by the PM circularly (Fig. 2), and abundant comb lines are generated. A total of 110 comb lines with 3-dB spectral power variation are obtained by adjusting the tunable optical fiber delay line to make each modulation in the fiber loop synchronous

(Fig. 4(a)). Figure 4(b) shows the subcarriers with optical spectrum ranging from 1 554 to 1 556 nm.

In conclusion, we present an OFC generation scheme based on TTF conversion and OFLM. Flat-top optical pulse train generated by intensity modulating a CWL is injected into an optical fiber loop. A total of 110 comb lines with 3-dB spectral power variation and 10-GHz frequency spacing are obtained by adjusting the optical delay line to make the phase delay for each round of the fiber loop $\theta = 2n\pi$. This scheme is simple and uses only one IM and one PM, which is a promising technique for arbitrary waveform generation and optical communications.

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