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Discussion

Generation of broadband optical frequency comb with rectangular envelope using cascaded intensity and dual-parallel modulators

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ABSTRACT

A novel approach using two cascaded intensity modulators and one single dual-parallel modulator to generate an optical frequency comb (OFC) is proposed and experimentally demonstrated. One broadband OFC with rectangular envelope can be achieved easily by adjusting the power of the microwave signals and the direct current bias applied to the modulators. The scheme is a relatively simple and low-power consumption solution for OFC generation, where specially tailored waveforms and high-power microwave signals are not used. In the experiment, 20 comb lines within 0.6 dB spectral power variation are obtained at 10 GHz microwave frequency. The experimental results agree well with the theoretical calculation.

1. Introduction

An optical frequency comb (OFC) composed of a series of equally spaced spectral lines has been driving a lot of applications, such as optical arbitrary waveform generation [1], microwave photonic filter [2], dense wavelength division multiplexing [3], and so on. Most of these applications demand an optical frequency comb with large bandwidth and flat spectral envelope. Although commercial mode-locked lasers or phase modulation of a continuous wave (CW) laser can create a large number of spectral lines, the spectral flatness of the generated OFC is quite poor, which is not suitable for the above applications.

Currently, there are various methods to generate a flat OFC by externally modulating a single laser source with microwave signals [4], such as phase modulation only [5], using one single dual-drive Mach–Zehnder modulator [6]. To generate more comb lines, more modulators were used in the OFC generator. Recently, using cascade polarization modulators, a 5 GHz comb with 25 lines within 1 dB power variation was generated [7]. However, the spacing of the comb was small and the bandwidth of the comb was limited. According to the time-to-frequency mapping technology [8], one 10-GHz comb with 38 comb lines in 1 dB bandwidth was obtained by cascaded intensity modulators and phase modulators [9], but the applied radio frequency (RF) signals must be tailored specially to generate a quadratic temporal phase. Using nonlinear medium for spectral broadening such as highly nonlinear fiber (HNLF) [10] or dispersion decreasing fiber (DDF) [11] is an alternative technique to scale the bandwidth of the comb, but the high power laser and special nonlinear medium must be employed for high effective nonlinear coefficient.

In this letter, we propose one novel scheme composed of two cascaded intensity modulators and one dual-parallel modulator (DPMZM) to generate a flat optical frequency comb. A comb of 20 lines within 0.6 dB spectral power variation is created experimentally by adjusting the power of the RF signals and the direct current (DC) bias applied to the modulators. The scheme is a relatively simple and low-power solution for OFC generation, where specially tailored waveforms and high-power microwave signals are not used. Moreover, this approach is extensible for a broader OFC with larger number of comb lines.

This work is structured as follows: We first review the research status of the OFCG in Section 1. Then the experimental principle and setup are presented in Section 2 and the experiment results are described in detail in Section 3. Finally, we conclude the work in Section 4.

2. Experimental principle and apparatus

The scheme of the proposed OFC generator is shown in Fig. 1. The bandwidth of the comb by externally modulating a single laser source is usually limited due to the modulation bandwidth of the modulator. To scale the bandwidth of the comb, we used two cascaded intensity modulators to create 4 spectral lines with wide

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comb spacing and equal power in the first stage of our scheme, as shown in the dotted part of Fig. 1. The spectrum evolution can be described as follows. First, a continuous wave (CW) laser was intensity modulated by one Mach–Zehnder modulator (MZM). When the DC bias of the MZM1 was set to zero, the output of the first MZM at point A had only carrier and even sidebands, which can be expressed as follows:

$$E_A = 2E_{in}\exp(jw_c t)[\sum_{n=-\infty}^{\infty} J_{2n}(\Gamma_1)\exp(j2nw_1 t)] \quad (1)$$

where E_{in} and w_c are the amplitude and angular frequency of the input optical signal respectively, $J_n(\cdot)$ is the nth-order of the Bessel function of the first kind, Γ_1 is the ratio of the amplitude of the applied RF signal to the half-wave voltage of the MZM1, and w_1 is the angular frequency of the applied RF signal. Due to the low power of the microwave signal, only the carrier and ± 2 sidebands are considered as seen in Fig. 2(a).

Then we set the bias of the second intensity modulator to π to achieve double side band with suppressed carrier (DSB-SC) modulation as seen in Fig. 2(b), where U and L mean the upper and lower sidebands with respect to the carrier respectively. The output at point B can be written as follows:

$$E_B = 4E_{in}\exp(jw_c t)J_1(\Gamma_2)[\sum_{n=\pm 1,\pm 3} E_n\exp(jnw_1 t)] \quad (2)$$

where Γ_2 is the ratio of the amplitude of the applied RF signal to the half-wave voltage of the MZM2, $E_1 = -E_{-1} = J_0(\Gamma_1) - J_2(\Gamma_1)$ and $E_3 = -E_{-3} = J_2(\Gamma_1)$.

If we let

$$J_0(\Gamma_1) = 2J_2(\Gamma_1) \quad (3)$$

we can get $|E_{\pm 3}| = |E_{\pm 1}|$. A spectrum of 4 lines with equal power was generated as shown in Fig. 2(c) and (d). Furthermore the spacing of the spectral lines was increased to $2f_1$, while the frequency of the RF signal was only f_1.

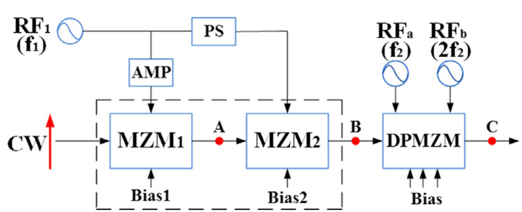

Fig. 1. Experimental setup for the OFC generator composed of two intensity modulators and one dual-parallel modulator (CW: continuous wave laser, MZM: Mach–Zehnder modulator, DPMZM: dual-parallel modulator, RF: radio frequency, PS: phase shifter, and AMP: amplifier).

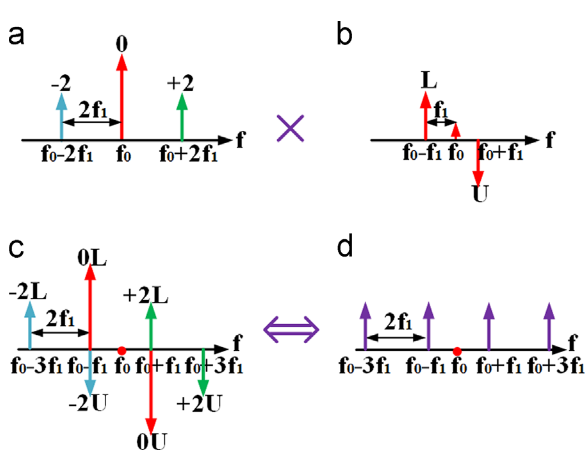

Fig. 2. Spectrum evolution of the first stage of the OFC generator (a: only MZM1 working, b: only MZM2 working, c: both MZM1 and MZM2 working, and d: corresponding power spectrum of c).

In the second stage of our scheme, two synchronized signals of frequencies f_2 and $2f_2$ were applied to the upper arm and lower arm of the DPMZM respectively as shown in Fig. 3. Only the carrier and ± 1 sidebands are considered owing to the low power of applied RF signals. If we set the ± 1 sidebands from the upper arm and lower arm having the same power as the power of the superposition of the two carriers, a spectrum of 5 lines with equal power will be created easily. When only one single DPMZM works, the amplitude of the carrier, the ± 1 and ± 2 sidebands of the output from the DPMZM can be expressed as follows:

$$E_{o0} = J_0(\Gamma_a)(1+\exp(j\varphi_a)) + J_0(\Gamma_b)(1+\exp(j\varphi_b))\exp(j\varphi_c) \quad (4)$$

$$E_{o+1} = -E_{o-1} = J_1(\Gamma_a)(1-\exp(j\varphi_a)) \quad (5)$$

$$E_{o+2} = -E_{o-2} = J_1(\Gamma_b)(1-\exp(j\varphi_b))\exp(j\varphi_c) \quad (6)$$

where $\Gamma_i = \pi V_i / V_{\pi i}(i=a,b)$, $\varphi_i = \pi V_{bias\_i}/V_{\pi i}(i=a,b,c)$, V_a and V_b are the amplitudes of the RF signals of frequencies f_2 and $2f_2$ respectively, $V_{bias\_i}(i=a,b,c)$ are the DC bias applied to MZM_i (i=a,b,c) and $V_{\pi i}(i=a,b,c)$ are the corresponding half-wave voltage of the modulators.

If we let

$$J_1(\Gamma_a) = 2J_0(\Gamma_a) \quad (7)$$

and set $V_{bias\_a} = V_{bias\_b} = V_{\pi a}/2$, $V_{bias\_c} = 0$, $V_a = V_b$, we can get $|E_{o0}| = |E_{o\pm 1}| = |E_{o\pm 2}|$. Then, a spectrum of 5 sidebands with equal power can be generated and the spectral spacing was set as f_2. In combination with the output of the first stage of the scheme, a comb of 20 lines with equal power and frequency separation was generated at last by adjusting f_1 and f_2 properly.

3. Experimental results

The setup shown in Fig. 1 was carried out to verify the proposed OFC generation scheme. One tunable laser with line width of 100 kHz (HP 81680A) is used and the optical spectrum of the OFC is measured by an optical spectrum analyzer (Advantest Q8384). In the experiment, first, we set $\Gamma_1 = 1.55$ to satisfy Eq. (3) and set $f_1 = 25$ GHz; 4 spectral lines with 50-GHz separation were created with 0.2-dB spectral power variation when only two cascaded intensity modulators worked, as shown in Fig. 4(a). All the other spectral lines were suppressed to at least 22-dB. Next, we set $\Gamma_a = 1.88$ to satisfy Eq. (7) and set $f_2 = 10$ GHz; 5 spectral lines with 10-GHz were obtained with 0.1-dB spectral power variation when only one DPMZM worked as seen in Fig. 4(b). All the other spectral lines were suppressed to at least 34-dB.

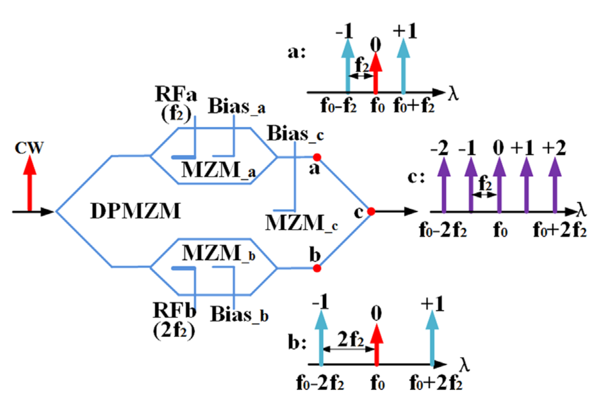

Fig. 3. Spectrum evolution of the second stage of the OFC generator when only one dual-parallel modulator worked (a: output of the upper arm of the DPMZM, b: output of the lower arm of the DPMZM, and c: power spectrum of the output of the DPMZM).