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Generation of optical frequency comb with large spectral lines by cascaded dual-parallel modulator and intensity modulators

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ABSTRACT

An optical frequency comb (OFC) generator with large and flat spectral lines based on cascaded dual-parallel modulator and intensity modulators is proposed and experimentally demonstrated. By adjusting the power of the microwave signals and the direct current bias applied to the modulators, 50 spectral lines with the comb flatness 1.38 dB can be generated. And the bandwidth of the optical frequency comb is broadened based on carriers cancellation of the DPMZM. The scheme is relatively simple and valuable, and the generated spectrums can be used for high capacity optical transmission systems in the future.

1. Introduction

Optical frequency comb (OFC) has many applications in optical communications such as dense wavelength division multiplexing (DWDM), optical orthogonal frequency division multiplexing(OOFDM), short optical pulse generation and arbitrary waveform generation [1–5]. In such applications the number of spectral lines, bandwidth, comb flatness and optical tone-to-noise ratio (OTNR) represent key considerations. A number of approaches have been proposed for optical frequency comb generation. Mode-locked lasers referenced to an external or internal optical reference can generate optical frequency combs with large bandwidth and high stability. However, this scheme always needs sophisticated control to achieve stable operation, and the center wavelength and frequency spacing are difficult to tune over a wide range [6]. OFC generation by externally modulating a single laser source with microwave signals is proved to be very economical and promising. Advantages of this method include the simple configuration, stable operation, adjustable wavelength, and precise comb spacing. There are several schemes that have been reported using Mach-Zehnder modulators and phase modulators [7–14]. To generate more comb lines, more modulators were used in the OFC generator, and the bandwidth of the OFC is limited by the modulation bandwidth of the modulator. In Ref. [7], the OFC of 100 light carriers with 25 GHz mode spacing is obtained by cascaded one IM and three PMs, where the IM is placed in front of the PMs. Another similar structure generated 60 and 75 lines with repetition rate combs spanning from 6 to 18 GHz, while the IM is placed behind the PMs in the paper [8]. Driven by tailored RF waveforms, the cascaded modulators can generate 38 tones within 1 dB spectral variation. But four modulators

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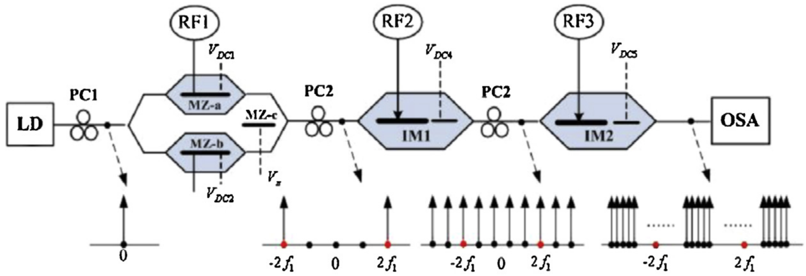

Fig. 1. Schematic diagram of the proposed optical frequency comb generator based on cascaded dual-parallel and intensity modulators. LD: laser diode. DPMZ: dual-parallel Mach–Zehnder modulator. IM: intensity modulator. RF: radio frequency. DC: dc power supply. PC: polarization control. OSA: optical spectrum analyzer.

must be employed and the applied radio frequency (RF) signals must be tailored specially to generate a quadratic temporal phase [9]. With cascaded IM and PM, 15 lines within 1 dB power variation or 17 lines within 3 dB power variation were reported in Ref. [10]. In this scheme, the number of the comb lines is in direct proportion to phase modulation index. But one phase modulator cannot be applied too large amplitude of sinusoidal waveform. A scheme using one intensity modulator and two phase modulators directly by sinusoidal waveform to generate an optical frequency comb is reported in Ref. [11]. 29 comb lines with spectral power variation less than 1.5 dB at 10 GHz were obtained. Recently 25 comb lines within 1 dB power variation were obtained by cascaded polarization modulators in Ref. [12]. But polarization modulator is expensive compared to intensity modulator. A 10 GHz comb with 20 comb lines within 0.6 dB spectral power variation can be achieved using two cascaded intensity modulators and one single dual-parallel modulator in Ref. [13], while the number of comb lines is relative less. In Ref. [14] the bandwidth of OFC is broadened using the FBG to suppress the carrier of the IM, which works at the maximum transmission point.

In this letter, we propose and experimentally demonstrate a scheme composed of cascaded dual-parallel and two intensity modulators to generate a flat and broadband optical frequency comb. The ±2th sidebands are generated at the output of the DPMZM with the carriers cancellation [15]. So we can achieve an OFC with 2 comb lines and the bandwidth of the OFC is four times of the applied microwave signal frequency. By adjusting the power of the microwave signal and the DC voltage applied to the intensity modulator, the amplitudes of the ±2th harmonic, the ±1th harmonic and carrier are equal. So we can achieve an OFC with 5 comb lines by single IM. And each of the two frequency components resulting from the DPMZM is modulated by the IM. This way, The 10 spectral lines of OFC are generated at the output of the first IM. By using another IM with the same work condition, it can also generate 5 flat comb lines. We can botain the 50 spectral lines of an OFC by modulating this structure, which is relatively simple and with a large number of comb lines.

2. Principle of analytical model

The schematic diagram of the proposed optical frequency comb generator which is performed using cascaded dual-parallel and two intensity modulators is shown in Fig. 1. The bandwidth of the OFC generated by externally modulating a continuous-wave (CW) laser source is limited by the modulation bandwidth of the modulator. To scale the bandwidth of the comb, we use DPMZ to generate ±2th harmonic and the spacing of the comb is four times of the frequency of the applied microwave signal. The DPMZM is an integrated structure which consists of three sub-MZMs, the parallel MZ-a and MZ-b are embedded in each arm of a main Mach–Zehnder (MZ) structure. The main modulator MZ-c is used for adjusting the optical phase difference between MZ-a and MZ-b. In this structure to generate OFC, The MZ-a is driven by the RF signal to operate at the maximum transmission point (MATP), the MZ-b is operated at short end with no RF signal applied, and the MZ-c is adjusted to introduce an extra π-phase difference between the output light wave of MZ-a and that of MZ-b. Setting the working voltage of the MZ-a to be 0 V, even sidebands (±2th sidebands and carrier) are generated. Assume that the field of optical source is defined as $E_{in}(t) = E_{in}\cos(\omega_c t)$, where E_{in} denotes the amplitude of the optical field, and ω_c is the angular frequency of the optical carrier. An electrical RF driving signal $V_1(t) = V_1 \sin(\omega_1 t)$ is applied to MZ-a, where V_1 and ω_1 are the corresponding amplitude and frequency of the microwave signal. When the MZ-a is biased at its maximum transmission point. The optical carriers of the output of the MZ-a can be expressed by

$$E_0(t) = \frac{1}{2}E_{in}\exp(j\omega_c t)J_0(m_1)$$

$$E_{\pm 2}(t) = \frac{1}{2}E_{in}\exp[j(\omega_c t \pm 2\omega_1 t)]J_2(m_1) \quad (1)$$

where $J_n(\cdot)$ denotes the nth-order Bessel function, $m_1 = \pi \times V_1/V_\pi$ is the RF modulation index. With no RF driving signal added onto MZ-b, the optical field at the output of the MZ-b can be expressed as

$$E_{MZ-b}(t) = \frac{1}{2}E_{in}\exp j(\omega_c t)\cos(\phi_{DC2}) \quad (2)$$