TUNABLE AND ULTRAFLAT OPTICAL FREQUENCY COMB GENERATOR BASED ON CASCADED INTENSITY MODULATORS

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An optical frequency comb generator based on two-cascade intensity modulators is proposed and experimentally demonstrated. By carefully adjusting direct current biases and drive amplitudes of radio frequency signals of the two intensity modulators, the combs consisting of 3, 5, 9, 15, or 25 lines with the relative amplitude flatness within 1 dB can be generated. The scheme is relatively simple and adjustable, where the frequency spacing varies with microwave frequency applied on modulators.

Key words: *Optical frequency comb, intensity modulator, optical communications.*

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Introduction

Optical frequency combs (OFC) have 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 (OAWG) [1–5]. In these applications, especially for OAWG, the number of comb lines, spectral flatness and optical tone-to-noise ratio (OTNR) represent key considerations.

Many schemes have been proposed for OFC generation.

Mode-locked lasers referred 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 large range [6].

OFC generation by externally modulating a single laser source with microwave signals is proved to be very economical. Advantages of this method include a simple configuration, stable operation, adjustable wavelength, and precise comb spacing. There are several methods that were reported using Mach–Zehnder modulators (MZM) and phase modulators (PM) [7–10]. Thus, nine lines within 2 dB power variation were obtained by two cascaded intensity modulators (IM) [7]. Driven by specially tailored RF waveforms, the cascaded modulator could generate 38 tones within 1 dB spectral variation. However, several (four) modulators must be employed here, and a very complex setting of microwave signals was applied [8].

With cascaded IM and PM, 15 lines within 1 dB power variation or 17 lines within 3 dB power variation were reported [9]. In this scheme, the number of the comb lines is in a direct proportion to the phase modulation index. But one phase modulator can't be applied too large amplitude of sinusoidal waveform.

A scheme using one intensity modulator and two phase modulators driven directly by sinusoidal waveform to generate an optical frequency comb was reported in [10]. There was obtained 29 comb lines with spectral power variation less than 1.5 dB. Here three modulators were used, with a corresponding cost increase.

Recently 25 comb lines within 1 dB power variation were obtained by cascaded polarization modulators [11]. However, the polarization modulators are more expensive as compared to the intensity ones.

In this article, we use two cascaded intensity modulators to obtain a tunable and ultraflat optical comb frequency. By carefully adjusting the

DC biases and the drive amplitudes of the RF signals of the two intensity modulators, 3, 5, 9, 15 and 25 comb lines with the comb flatness within 1 dB can be generated.

Analytical model

A schematic diagram of the proposed optical frequency comb generator which uses two cascaded Mach–Zehnder intensity modulators is shown in Fig. 1.

Two intensity modulators IM1 and IM2 are biased at V_{dc1} and V_{dc2}, respectively. The RF driving signals $V_1(t) = V_1 \sin(\omega_1 t)$ and $V_2(t) = V_2 \sin(\omega_2 t)$ are applied to IM1 and IM2, where V_1 and V_2 are the amplitudes of the input RF signals with the frequencies of ω_1 and ω_2, respectively.

Assuming that the field of the optical source is $E_{in}(t) = E_0 \cos(\omega_0 t)$, where E_0 denotes the amplitude of the optical field, and ω_0 is the angular frequency of the optical carrier, the optical field at the output of the IM1 can be expressed by

$$E_{out1}(t) = (E_{in}/2) \sum_{n=-\infty}^{+\infty} [J_n(m_1)\exp(jn\omega t + j\varphi_1) + J_n(-m_1)\exp(jn\omega t - j\varphi_1)], \quad (1)$$

where J_n denotes the n^{th}-order Bessel function of the first kind; $m_1 = \pi V_1/V_\varpi$ is the RF modulation index; $\varphi_1 = \pi V_{dc1}/V_\pi$ is the phase shift caused by the DC voltage applied to IM1, and V_π is the half-wave voltage.

Thus the expressions for carriers are

$$E_{0,0} = \left(E_0/2\right) J_0(m_1)[\exp(j\varphi_1) + \exp(-j\varphi_1)]\cos(\omega_0 t),$$

$$E_{0,1} = \left(E_0/2\right) J_1(m_1)[\exp(j\varphi_1) + \exp(-j\varphi_1)] \times \times\cos[(\omega_0 + \omega_1)t],$$

$$E_{0,-1} = \left(E_0/2\right) J_{-1}(m_1)[\exp(j\varphi_1) + \exp(-j\varphi_1)] \times \times\cos[(\omega_0 - \omega_1)t],$$

$$E_{0,1} = \left(E_0/2\right) J_2(m_1)[\exp(j\varphi_1) + \exp(-j\varphi_1)] \times \times\cos[(\omega_0 + 2\omega_1)t], \quad (2)$$

$$E_{0,-2} = \left(E_0/2\right) J_1(m_1)[\exp(j\varphi_1) + \exp(-j\varphi_1)] \times \times\cos[(\omega_0 - 2\omega_1)t],$$

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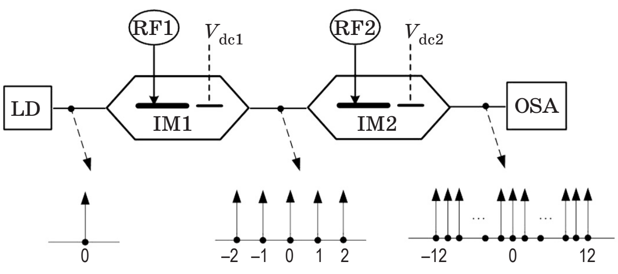

Fig. 1. Schematic diagram of the proposed optical frequency comb generator based on cascaded intensity modulators. LD: laser diode, IM: intensity modulator, RF: radio frequency, DC: dc power supply, OSA: optical spectrum analyzer.

The amplitudes of the n^{th} and ($-n^{th}$) harmonics are equal, $|J_n(m_1)| = |J_{-n}(m_1)|$.

Let us assume $|E_{0,0}| = |E_{0,-1}| = |E_{0,1}|$, than

$$J_0(m_1)[\exp(j\varphi_1) + \exp(-j\varphi_1)] = J_1(m_1)[\exp(j\varphi_1) - \exp(-j\varphi_1)]. \quad (3)$$

By appropriate adjusting the DC bias and the drive amplitudes of the RF1, three (3) flat spectral lines can be generated. For instance, when $m_1 = 0.5$ and $\varphi_1 \approx 1.32$, or $m_1 = 0.3$ and $\varphi_1 \approx 1.32$, the equation (3) can be satisfied.

If we assume $|E_{0,-2}| = |E_{0,2}| = |E_{0,0}| = |E_{0,-1}| = |E_{0,1}|$, than

$$J_0(m_1) = J_2(m_1), \quad (4)$$

$$J_0(m_1)[\exp(j\varphi_1) + \exp(-j\varphi_1)] = J_1(m_1)[\exp(j\varphi_1) - \exp(-j\varphi_1)]. \quad (5)$$

With $m_1 = 1.84$ and $\varphi_1 \approx 0.5$, the equations (4) and (5) can be satisfied.

So by adjusting two parameters, viz. the RF modulation index m_1 and the phase shift φ_1 caused by the DC bias, five (5) flat spectral lines can be generated.

When cascading with another intensity modulator IM2, the output of optical signal from the IM1 can be sent to the IM2 driven by a RF signal with a frequency that is one fifth or one third of that of RF1. Based on the same principle as described above, each spectral line can generate another 5 or 3 spectral lines by IM2. So an optical frequency comb can be generated with a variable number of comb lines such as 9, 15, and 25. To ensure the phase correlation between the spectral lines, the RF1 can be generated by applying a frequency multiplier to the RF2.

Simulation results and discussions

Computer simulations using a software package from Virtual Photonics Inc. were performed to investigate the performance of our proposed

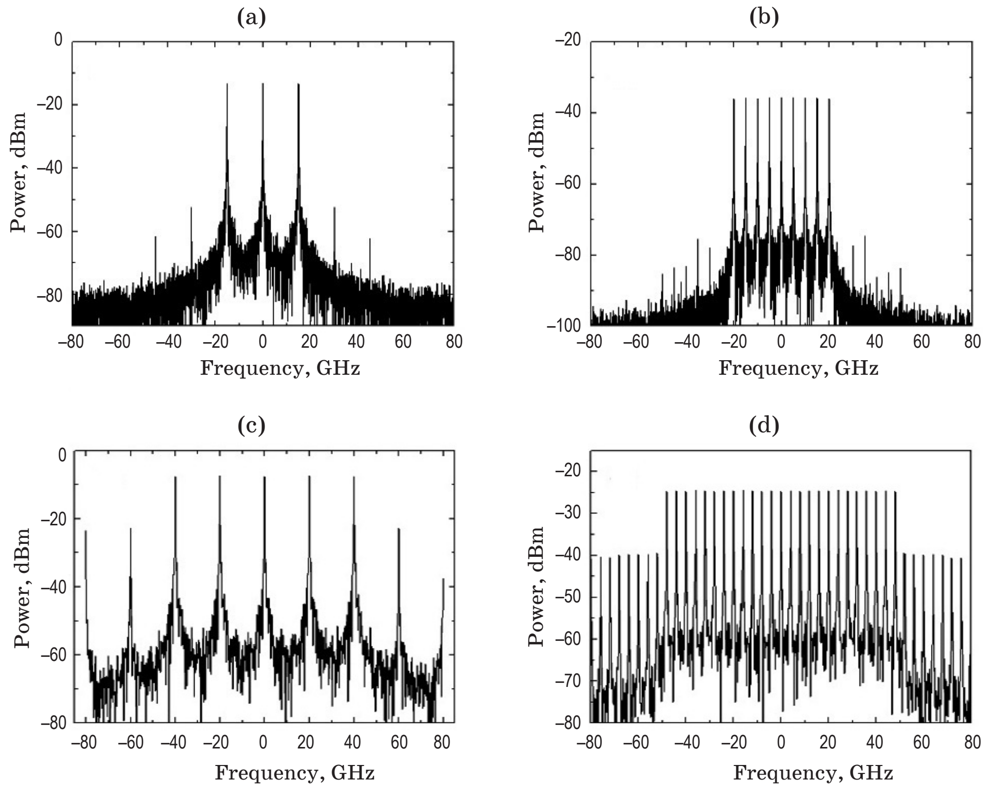

Fig. 2. Simulated output spectrum of optical carrier with 3(a), 9(b), 5(c), and 25(d) comb lines. Abscissa axis: the comb frequency (GHz) relative to 193.1 THz.

optical frequency comb generation technique. In the simulation, a CW laser with a line width of 10 MHz at a frequency of 193.1 THz was sent to the cascaded intensity modulators. The intensity modulators operated with the same half-wave voltage of 3.2 V and the same extinction ratio of 30 dB. The frequency RF1 was equal to 15 GHz.

To satisfy (3), the DC bias and the drive amplitudes of the RF1 were adjusted to 0.30 V and 1.45 V, respectively. We could get three (3) flat spectral lines with the spacing of 15 GHz as shown in Fig. 2a. The power variation was within 0.02 dB, and the side-comb suppression ratio (SCSR) was 39.1 dB.

When cascaded with IM2, which had the same DC bias and RF amplitude, and the frequency of RF2 equal to 5 GHz, nine (9) comb lines with flatness less than 0.35 dB could be obtained (Fig. 2b), with SCSR = 29.7 dB.

To satisfy (4) and (5), the frequency and amplitude of RF1 were adjusted to 15 GHz and 2.93 V, respectively. The DC voltage applied to IM1 was 0.79 V. We could get five (5) flat spectral lines with the spacing of 15 GHz by IM1. The power variation was within 0.11 dB, and the SCSR was 15.15 dB (Fig. 2c).

When cascaded with IM2 with the same DC bias and RF amplitude as IM1, 25 comb lines with flatness less than 0.35 dB were obtained (Fig. 2d), with SCSR = 15.37 dB.

In addition, our scheme has the capability of arbitrarily selecting a number of comb lines in the range 3, 5, 9, 15, and 25, by adjusting the drive amplitudes of both RF signals and both DC bias. The simulated results containing various system parameters are summarized in the table. This feature can be used to realize a flexible dynamic bandwidth allocation in optical OFDM transmission system. The corresponding simulated spectra for 15 comb line are shown in Fig. 3.

The flatness of our frequency comb is determined by the values of the RF modulation index m and the DC bias.

For example, the variations of the flatness with the RF modulation index m_1 and the phase shift φ_1 used by the DC bias for 25 comb lines are shown in Fig. 4a and 4b, respectively. We can see that there are optimum values for m_1 and φ_1 to obtain the best values of the OFC flatness defined as the difference of the maximum and minimum power of OFC. From Fig. 4a, we can find that

System parameters for flexible comb generation

Number of comb lines	3	5	9	15	25
Frequency of RF1, GHz	15	15	15	15	15
Frequency of RF2, GHz	–	–	5	5	3
Drive amplitude of RF1 (V_1)	0.095	0.93	0.095	0.93	0.93
Drive amplitude of RF2 (V_2)	–	–	0.095	0.095	0.93
DC bias of RF1 (V_{dc1})	0.45	0.31	0.45	0.31	0.31
DC bias of RF2 (V_{dc2})	–	–	0.45	0.45	0.31
Flatness, dB	0.02	0.11	0.35	0.34	0.35
SCSR, dB	39	15	30	14	15

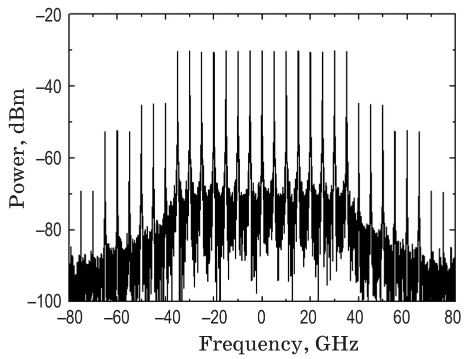

Fig. 3. Simulated output spectrum for 15 lines. Abscissa axis: the comb frequency (GHz) relative to 193.1 THz.

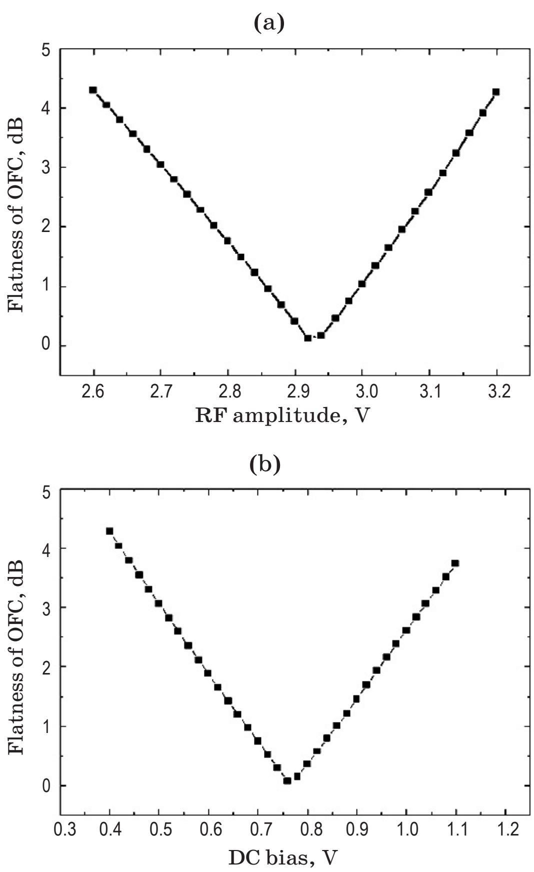

Fig. 4. Four relations between the flatness of OFC and the RF amplitude (a) and the DC bias (b).

at $m_1 \approx 1.84$ and the phase shift caused by DC bias $\varphi_1 \approx 0.5$, the flatness of OFC reaches its extremum.

Experimental results

We experimentally demonstrated the scheme shown in Fig. 1.

In the experiment, the center wavelength of CW laser is 1550 nm, and the half-wave voltage of two intensity modulators is both 3.2 V. Fig. 5 shows the optical spectrum measured by an optical spectrum analyzer (Advantest Q8384) with resolution of 0.01 nm. By adjusting the amplitude of RF1 and the DC1, the OFC with three (3) lines is obtained as shown in Fig. 5a. It can be seen that the generated three tone carriers are with superior flatness. The power variation is within 0.5 dB, and the side-comb suppression ratio (SCSR) is 50 dB.

Fig. 5b shows the optical spectrum of the generated optical frequency comb with five (5) lines. The power variation is within 1 dB, and SCSR is 15 dB.

The measured spectra for combs with 9, 15, and 25 lines which are generated by two cascaded intensity modulators are shown in Fig. 5(c–e). The power variation is within 0.5 dB and SCSR is 30 dB for nine (9) comb lines.

From Fig. 5d, it can be seen that the generated 15 tone carriers are within 1 dB flatness and SCSR = 17,4 dB.

Twenty-five comb lines with 1dB power variation and SCSR = 13 dB are shown in Fig. 5e.

Conclusion

The OFC generator that uses two cascaded intensity modulators was demonstrated experimentally and studied theoretically. A good agreement between the experiment and simulation was obtained. By carefully adjusting the DC biases and the drive amplitudes of the RF signals of the two intensity

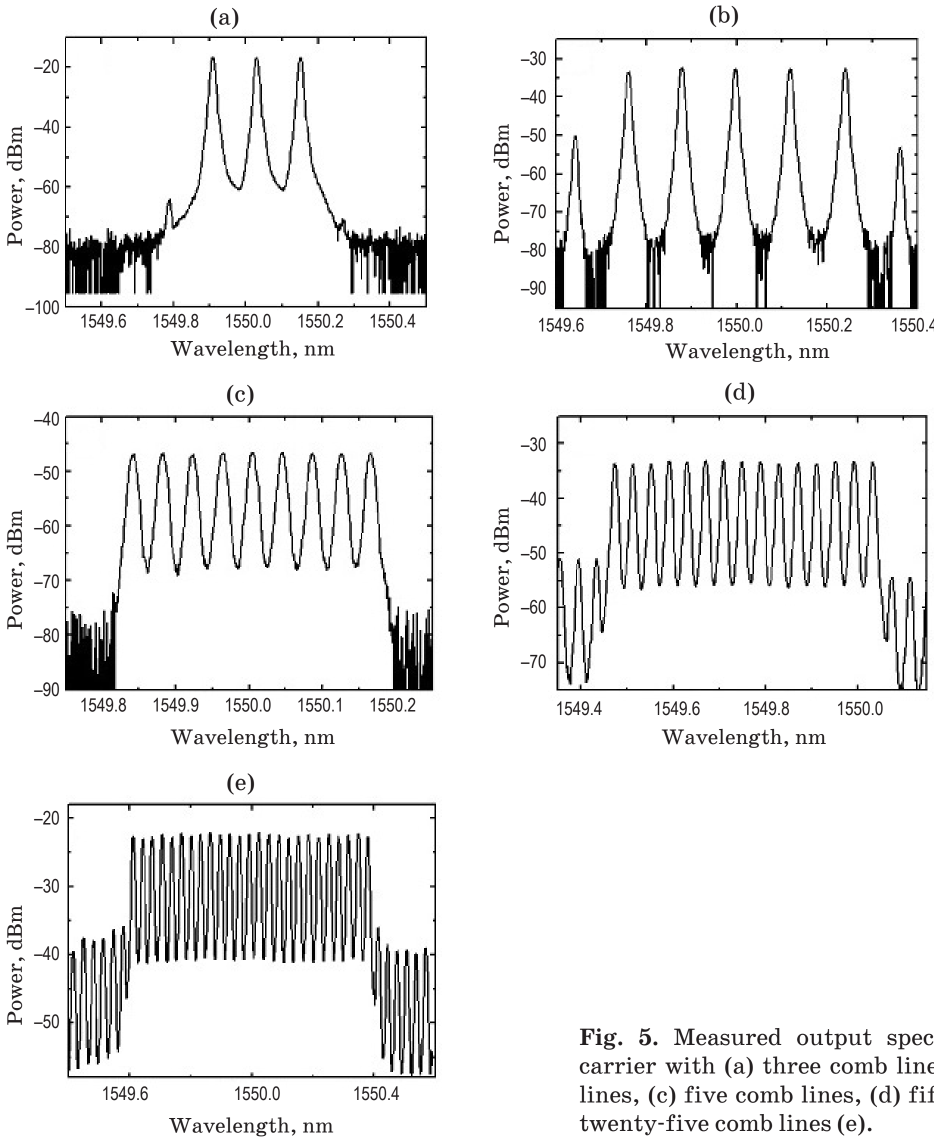

Fig. 5. Measured output spectrum of optical carrier with (a) three comb lines, (b) nine comb lines, (c) five comb lines, (d) fifteen comb lines, twenty-five comb lines (e).

modulators, as many as 3, 5, 9, 15, and 25 comb lines with the comb flatness within 1 dB could be generated. The scheme was relatively simple and adjustable, where the frequency spacing varying with microwave frequency applied on modulators.

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