Generation of optical comb frequency signal with high spectral flatness using two cascaded optical modulators

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Abstract: We experimentally demonstrate a new scheme to generate comb frequency signal showing high spectral flatness with low driving power based on two cascaded optical modulators.

OCIS codes: (060.4510) Optical communications; (060.5625) Radio frequency photonics; (060.4080) Modulation.

1. Introduction

The generation of comb frequency signal with narrow channel spacing is an attractive solution for super-dense wavelength-division multiplexed (SDWDM) systems [1-3]. One of the promising schemes is to use optical modulation technique [1-5], where multiple optical carriers with precise channel spacing can be obtained from one seed light source, showing the advantages of flexibility and scalability. However, in these reports, the power variation among the generated 9 carriers is more than 1.6 dB with >27-dBm radio frequency (RF) driving power needed. In practice, the insufficient spectral flatness could degrade the performance of the SDWDW systems, while the commercially available RF amplifiers with > 27-dBm output power in the ten gigahertz frequency range are costly. In this paper, we propose a new scheme to produce a comb signal using a dual-parallel Mach-Zehnder modulator (DPMZM) [6] assisted by a single-drive Mach-Zehnder modulator (SDMZM). ~0.8-dB spectral flatness is obtained, while the required RF amplitude is only ~10 V. To the best of our knowledge, it is the highest spectral flatness with the lowest RF power based on the optical modulation approach to generate the same number of carriers. Therefore, in terms of RF driving power and spectral flatness, our scheme appears to be more attractive and effective. Error-free 1.25-Gb/s data transmission using the generated multi-carrier is also performed over a 25-km fiber.

2. Principle

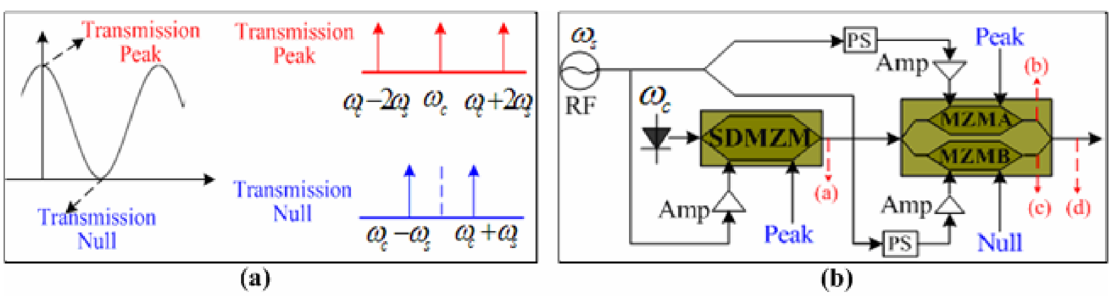

Fig. 1. (a)Tones generated by one SDMZM; (b) Schematic diagram of comb signal generation.

Figure 1(a) depicts the tones generated by a SDMZM under two different bias conditions. The SDMZM is driven by an RF signal $\varepsilon V\pi + \alpha V\pi cos(\omega_s t)$, where ε and are the bias voltage of the modulator and the amplitude of the modulating signal normalized to the half-wave voltage Vπ, respectively. The output field of the MZM can be described as [7]:

$$E_{out}(t) = J_0\left(\alpha\frac{\pi}{2}\right)\cos\left(\varepsilon\frac{\pi}{2}\right)\cos(\omega_c t) + \sum_{k=1}^{\infty}\left\{(-1)^k J_{2k-1}\left(\alpha\frac{\pi}{2}\right)\sin\left(\varepsilon\frac{\pi}{2}\right)\cos\left[\omega_c t \pm (2k-1)\omega_s t\right] + (-1)^k J_{2k}\left(\alpha\frac{\pi}{2}\right)\cos\left(\varepsilon\frac{\pi}{2}\right)\cos[\omega_c t \pm 2k\omega_s t]\right\} \quad (1)$$

where ω_c and ω_s are the angular frequencies of the optical carrier and the modulating signal, respectively. $J_x(\cdot)$ is the coefficients of Bessel function of the first kind, and $k = 1, 2, 3, \ldots$ When ε = 0, i.e., the bias is set at the peak of the transmission curve, the odd-order sidebands are suppressed. Since the amplitudes of the generated tones are proportional to $J_x(\alpha\cdot\pi/2)$, the frequency components at the optical carrier and at the two second-order harmonics can achieve adequate amplitude while the higher-order sidebands remain negligible by properly controlling the driving voltage, as shown in Fig. 1(a). On the other hand, if ε = 1, i.e., the modulator is biased at the transmission null, the even-order sidebands including the optical carrier can be suppressed. If the SDMZM is cascaded by a DPMZM, a comb signal can be generated. Figure 1(b) shows the generation process. An RF signal is split into three parts, which are used to drive the SDMZM and the DPMZM, respectively. The SDMZM is biased at the transmission peak to generate 3 tones. The output signals of the SDMZM are injected into the following DPMZM. The sub-MZMA is biased at the peak to output 5 frequency components ($\omega_c, \omega_c \pm 2\omega_s,\ \omega_c \pm 4\omega_s$) with a frequency spacing of twice the RF frequency. The sub-MZMB is biased at the null to obtain 4 frequency components ($\omega_c \pm \omega_s, \omega_c \pm 3\omega_s$) with the same frequency spacing. Since the DPMZM combines the output signals from the two sub-MZMs, the output field of the DPMZM can be described as [8]:

$$E_{out\_DPMZM}(t) = E_{out\_MZMA}(t)\exp(j\frac{\pi}{2}\cdot V_{bias\_c}/V_{\pi c}) + E_{out\_MZMB}(t)\cdot\exp(-j\frac{\pi}{2}\cdot V_{bias\_c}/V_{\pi c}) \quad (2)$$

where E_{out_MZMA} and E_{out_MZMB} are the output fields of the two sub-modulators, $V_{bias\text{-}c}$ and $V_{\pi c}$ are the bias and half-wave voltage of the main modulator of the DPMZM, respectively. Hence, the output of the DPMZM contains 9 tones ($\omega_c \pm i\omega_s, i = 0,1\cdots 4$) with a channel spacing equal to the RF frequency. There are 6 parameters in the formula (2) that can be optimized to achieve flat spectral response: the amplitudes of the three RF signals, the phase differences of SDMZM and two sub-modulator of the DPMZM, and the bias voltage of the main modulator in the DPMZM. By properly adjusting these parameters, a comb signal of 9 tones with high spectral flatness can be obtained.

3. Experimental Setup and Results

To verify the feasibility of the proposed scheme, we perform an experiment as shown in Fig. 1(b). A continuous wave (CW) signal from a tunable laser at 1549.89 nm is fed into a SDMZM (JDS Uniphase, 4.5-dB insertion loss, V_π = 5.5 V at 1 GHz), which is biased at the peak and driven by a 10-GHz clock signal to produce 3 tones. The clock signal is amplified to ~10-V peak-to-peak value to ensure the almost same powers of the three tones while other higher-order components are suppressed. Fig. 2(a) shows the spectrum, where the 3 tones have nearly the same amplitudes and the higher-order tones are 20 dB lower. The output signals of the first modulator are then injected into a following 10-GHz DPMZM (COVEGA Mach-10060, 5.8-dB insertion loss). The V_π of the two sub-MZMs is 5.6 V at direct current and that of the main MZM is 5.2 V. The sub-MZMA is biased at the peak and driven by a 10-GHz clock signal with ~8-V peak-to-peak voltage to generate 5 tones with a 20-GHz frequency spacing, while the sub-MZMB is biased at the null and driven by a 10-GHz clock signal with ~5.5-V peak-to-peak voltage to produce 4 tones with a 20-GHz frequency spacing. By controlling the RF amplifiers and the phase shifters to set the proper amplitudes and phases of the RF signals, the generated frequency components have nearly the same powers, as

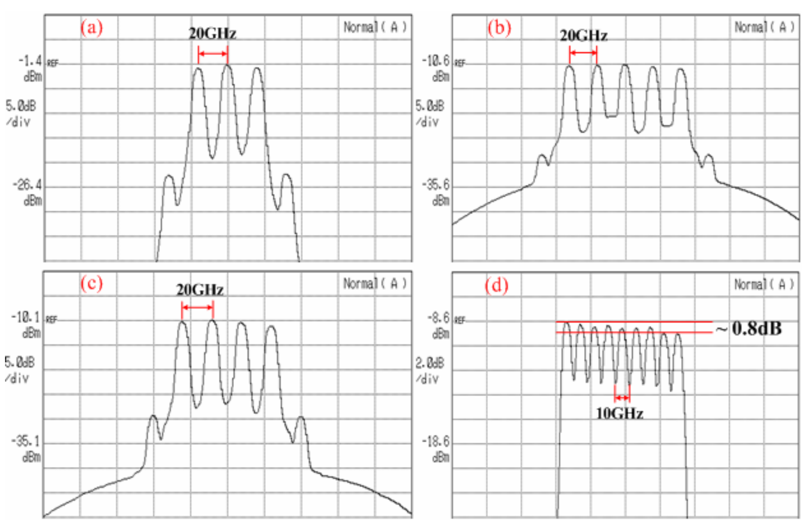

Fig. 2. Optical spectra taken at different positions as indicated in Fig. 1(b).
Y-axis scale of (a), (b) and (c): 5 dB/div; Y-axis scale of (d): 2 dB/div.

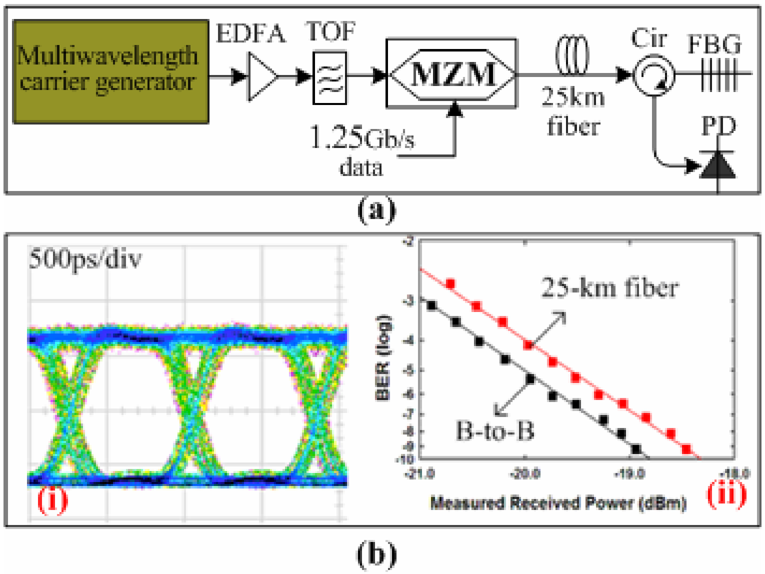

Fig. 3. (a) Experimental setup of the transmission. (b-i)Eelectrical eye diagram; (b-ii) BER performance.

shown in Fig. 2(b) and (c), respectively. The output of the DPMZM combining two sub-MZMs is further optimized by adjusting the bias of the main modulator to produce a comb signal including 9 tones with a 10-GHz frequency spacing. Figure 2(d) indicates the spectrum with ~0.8-dB optical power variation among channels.

We also test the transmission performance for a SDWDM system using the generated comb signal, which is modulated by a 1.25-Gb/s pseudorandom bit sequence (PRBS) data with a word length of 2^{31}-1 to produce an amplitude shift keying (ASK) format. The experimental setup is shown in Fig. 3(a). After transmission over a 25-km single mode fiber (SMF), a circulator with a fiber Bragg grating (FBG) is used to filter the $\omega_c+4\omega_s$ frequency component, which is then detected by a 2.5-GHz PIN. The electrical eye diagram is shown in Fig. 3 (b-i). Figure 3(b-ii) indicates the measured bit-error-rate (BER) performance, and a power penalty of ~0.5 dB is observed, which can be attributed to the chromatic dispersion in RF frequency band after the 25-km fiber.

4. Conclusion

We have experimentally demonstrated that the comb signal can be generated using one SDMZM and DPMZM from a single seed light source, where 9 carriers with a spectral flatness of better than 0.8 dB are obtained. The 1.25-Gb/s ASK is also successfully transmitted over the 25-km with ~0.5-dB power penalty based on the obtained comb signal.

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