Sextuple-frequency two-tone signal generation using two cascaded Mach-Zehnder modulators for multiple harmonics cancelling

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Abstract: We propose a novel sextuple-frequency two-tone signal generation method using two cascaded Mach-Zehnder modulators (MZMs). The first MZM is used to generate a large third-order harmonics component with a large RF input of 4.64V\(_{\text{pp}}\) (peak-to-peak). The second MZM is used to suppress first- and fifth-order unwanted harmonics at the same time. The proposed method was investigated by numerical simulations and experiments. We successfully suppressed the unwanted harmonics to less than ~21 dB of the intended third-order harmonics by using two MZMs with extinction ratios of 23 dB and 26 dB.

Keywords: two-tone signal, Mach-Zehnder modulator, radio-over-fiber

Classification: Wireless Communication Technologies

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1 Introduction

Two-tone signal generation is a key aspect of Radio-over-Fiber (RoF) systems, which are one of the basic technologies for high-speed wireless network systems. One method for achieving two-tone signal generation is double-sideband suppressed carrier (DSB-SC) optical modulation using a Mach-Zehnder modulator (MZM), where a lightwave is modulated by a radio frequency (RF) sinusoidal signal [1]. However, modulation using an MZM also generates high-order unwanted harmonics due to the nonlinearity of the modulator, and these distort the output signal. Various techniques have been reported for suppressing unwanted harmonics components. One method employs optical filtering to cut the unwanted frequency components [2, 3]. Other methods include using multiple MZMs connected in parallel [4, 5, 6] and/or in series [2, 7, 8, 9]. In these studies, unwanted harmonics components were suppressed, one-by-one, using additional MZMs. In our previous study, we proposed and investigated a novel sextuple-frequency two-tone signal generation method using two cascaded single MZMs, in which the additional MZM was used to suppress first- and fifth-order unwanted harmonics components at the same time [10]. In the preliminary experiment, however, we used two cascaded dual-parallel MZMs (DP-MZMs), because of the lack of available single MZMs. One DP-MZM was used as a single MZM by killing one sub-MZM in the DP-MZM by adjusting the bias point to the bottom. However, this experimental setup causes some small errors in the results due to the limited extinction ratio of the killed MZM. In this paper, we performed an experiment using two single MZMs. Furthermore, we investigated the effect of the limited extinction ratio of the MZMs by numerical simulations. We successfully suppressed the unwanted harmonics to less than $-21$ dB of the intended third-order harmonics, using the two MZMs with extinction ratios of 23 dB and 26 dB.
2 Principle

Figure 1 shows the setup of our proposed sextuple-frequency two-tone signal generation system [10]. MZM1 is biased at the bottom point and is driven by a sinusoidal RF signal with an angular frequency $\omega$. The output of MZM1, $E_{\text{out}1}(t)$, is expressed as

$$E_{\text{out}1}(t) = E_{\text{in}}(t)\left[\frac{j}{2} \exp(j \frac{\pi}{2V_{\pi}} V_A \cos \omega t) - \frac{j}{2} \exp(-j \frac{\pi}{2V_{\pi}} V_A \cos \omega t)\right],$$

(1)

where $E_{\text{in}}(t)$, $V_{\pi}$, and $V_A$ are the amplitude of the optical electric field of the input lightwave, the half wavelength voltage, and the amplitude of the RF signal, respectively. Here, we need large third-order harmonics to achieve a sextuple-frequency two-tone signal. Using Eq. (1) and the Jacobi–Anger expansion, the maximum third-order harmonic occurs when $V_A$ is about $2.68V_{\pi}$. However, unwanted harmonics are also generated at the same time, as shown in Fig. 2(a). MZM2 is biased at the top point and is driven by a sinusoidal RF signal whose phase is $\pi/2$-shifted from that for MZM1. The output of MZM2, $E_{\text{out}2}(t)$, is expressed as

$$E_{\text{out}2}(t) = E_{\text{out}1}(t)\left[\frac{1}{2} \exp(j \frac{\pi}{2V_{\pi}} V_B \sin \omega t) + \frac{1}{2} \exp(-j \frac{\pi}{2V_{\pi}} V_B \sin \omega t)\right],$$

(2)

where $V_B$ is the amplitude of the RF signal for MZM2. Using Eq. (2) with the Jacobi–Anger expansion, the condition for cancelling the first-order harmonics can be expressed as

$$J_{-1}(x_a)J_2(x_b) + J_3(x_a)J_{-2}(x_b) + J_{-5}(x_a)J_4(x_b) + J_6(x_a)J_{-6}(x_b) + J_1(x_a)J_0(x_b) + J_{-3}(x_a)J_4(x_b) + J_5(x_a)J_{-4}(x_b).$$

(3)
The condition for cancelling the fifth-order harmonics can be expressed as

\[
J_{-1}(x_a)J_0(x_b) + J_3(x_a)J_2(x_b) + J_7(x_a)J_{-2}(x_b) = J_1(x_a)J_4(x_b) + J_5(x_a)J_0(x_b) + J_9(x_a)J_{-4}(x_b),
\]

where \( J_n(x) \) is the \( n \)-th order Bessel function of the first kind. Here, \( x_a \) and \( x_b \) are given by

\[
x_a = \frac{V_A}{2V_\pi},
\]

\[
x_b = \frac{V_B}{2V_\pi}.
\]

Using numerical simulation, we searched \( V_A \) and \( V_B \) around the point \( V_A = 2.68V_\pi \) which maximizes the third-order harmonics. Consequently, we found that Eqs. (3) and (4) are satisfied at the same time when \( V_A \) is about 2.32V_\pi (peak-to-peak amplitude: 4.64V_\pi) and \( V_B \) is about 0.74V_\pi. Using this condition, the first- and fifth-order harmonics components are canceled at the same time, as shown in Fig. 2(b).

3 System setup

The numerical simulations and experiments were performed using the system setup shown in Fig. 1. A lightwave with a wavelength of 1549 nm (193.5 THz) was modulated by two cascaded MZMs, MZM1 and MZM2, which were driven by 10 GHz RF signals. The phase of the RF signal for MZM2 was controlled using a phase shifter (PS). An amplifier (Amp) and an attenuator (ATT) were used to adjust the amplitude of the RF signals. The bias points of the MZMs were adjusted while observing the optical spectrum of the output lightwave using an optical spectrum analyzer (OSA) (Anritsu, MS9710C, 0.05 nm resolution). The extinction ratios of MZM1 and MZM2 used in the experiment were 23 dB and 26 dB, respectively.

4 Results and discussion

Figures 3(a) and (b) show the results of the numerical simulations of our proposed method assuming that the extinction ratios of the MZMs were infinite. Figure 3(a) shows the optical spectrum when only MZM1 was used. First-, third-, fifth-, and seventh-order harmonics are observed in the figure. The power level of the third-order harmonics was the largest of the generated harmonics components, thanks to the large modulation amplitude for MZM1. The power levels of the first- and fifth-order harmonics were about –14 dB and –13 dB smaller than the required third-order harmonics, respectively. By using MZM2, however, the first- and fifth-order harmonics could be suppressed to the noise level, as shown in Fig. 3(b). Figures 3(c) and (d) show the results of the simulations assuming that the extinction ratios of MZM1 and MZM2 were 23 dB and 26 dB, respectively. Figure 3(c) shows the optical spectrum when only MZM1 was used. Due to the limited extinction ratio, the carrier and even-order harmonics were observed. Figure 3(d) shows the optical spectrum when MZM1 and MZM2 were both used. We could successfully suppress the power levels of the unwanted harmonics to 21 dB smaller than the required third-order harmonics. Figures 3(e) and (f) show the experimental results. Figure 3(e)
shows the result when only MZM1 was used. Figure 3(f) shows the result when MZM1 and MZM2 were both used. The observed spectra were almost identical to the results of the numerical simulations in Figs. 3(c) and (d). The unwanted harmonics components were suppressed to 21 dB smaller than the required third-order harmonics.

![Fig. 3. Optical spectra of output lightwaves and suppression of unwanted high-order harmonics components.](image)

5 Conclusion

We proposed and investigated a novel method for generating a sextuple-frequency two-tone signal using two cascaded MZMs. The performance was investigated by
numerical simulations and experiments. In the method, two unwanted harmonics components could be suppressed at the same time, using only one additional cascaded MZM.