Quadruple-frequency optical two-tone signal generation using a DP-QPSK modulator

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Abstract: We investigate a novel frequency-quadruple optical two-tone signal generation method using a DP-QPSK modulator, which includes four Mach-Zehnder modulators (MZMs). One MZM is used to generate a basic two-tone signal. The other MZMs are used to compensate unwanted high-order harmonics and carrier components of the generated signal. In the experiment, a two-tone signal was successfully generated, and the power levels of fourth-order harmonics and the carrier were reduced to levels 36.8 dB and 40.3 dB smaller than the required signal, respectively. We also evaluated suppression ratio of the unwanted components against fluctuations of amplitude and bias voltages for the MZMs.

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

Classification: Wireless Communication Technologies

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1 Introduction

Radio-over-fiber (RoF) is regarded as one of the important technologies that can meet the increasing demand for higher transmission speeds on broadband wireless communication networks. One key aspect of RoF is the generation of a two-tone lightwave signal. An optical two-tone signal can be generated by using a Mach-Zehnder modulator (MZM); however, one problem with this method is that nonlinearity and an asymmetric splitting ratio in the MZM increase unwanted high-order harmonics of the generated two-tone signal, which cause waveform distortion. Some methods for suppressing unwanted high-order harmonics have been studied [1, 2, 3, 4, 5, 6, 7, 8]. One simple method employs MZMs connected in series to suppress the third-order harmonics component [1]. Some methods employ specially designed MZMs with a high extinction ratio [2, 3, 4], and some use dual-parallel MZMs (DP-MZMs) to suppress unwanted third-order harmonics components [5, 6, 7, 8]. In our previous work, we proposed a novel frequency-quadruple two-tone signal generation method using a commercially available dual-polarization quadrature phase shift keying (DP-QPSK) modulator that consists of four MZMs [9]. In this method, second-order harmonics are used to generate a quadruple-frequency optical two-tone signal. The unwanted carrier and first- and fourth-order harmonics components are suppressed using the DP-QPSK modulator at the same time. In this paper, we demonstrate the effectiveness of the proposed method by numerical simulation and an experiment. The principle is clarified using Bessel functions. Suppression performance of the unwanted carrier and harmonics components was evaluated by the experiment. Furthermore, we evaluated suppression ratio of the unwanted components against fluctuations of amplitude and bias voltages for the MZMs.

2 Principle

Fig. 1(a) schematically shows our proposed frequency-quadruple two-tone signal generation method in which a DP-QPSK modulator is used [9]. The DP-QPSK modulator includes four MZMs, namely MZM1, MZM2, MZM3, and MZM4. The radio frequency (RF) signals used to drive the four MZMs are expressed as
\[ \begin{align*}
v_1(t) &= A_1 \sin(2\pi f_s t), \\
v_2(t) &= A_2 \sin(2\pi f_s t), \\
v_3(t) &= A_3 \sin(4\pi f_s t), \\
v_4(t) &= 0,
\end{align*} \]

where \(A_n\) is the amplitude of the RF signal used to drive the \(n\)-th MZM. MZM3 is driven by an RF signal with a frequency \(2f_s\), whereas MZM1 and MZM2 are driven with frequency \(f_s\). MZM4 is used to suppress the carrier, controlling only the bias point. The two-tone signal is basically generated by MZM1. An input lightwave is modulated by an RF signal \(f_s\) in MZM1, which is biased at the point of top. Here, MZM1 is driven by an RF signal with an amplitude of \(V_{\pi}/\sqrt{2}\), where \(V_{\pi}\) is the half-wave voltage, to achieve maximum optical power. However, the two-tone signal generated by MZM1 includes a carrier component and high-order harmonics, which distort the generated sinusoidal waveform. Fig. 1(b) schematically shows the optical spectrum generated by MZM1. MZM2 is biased at the bottom point and is driven with frequency \(f_s\). Fig. 1(c) shows the optical spectrum of the output of MZM2. The first-order harmonics of MZM1 are canceled by the output of MZM2, while adjusting the driving amplitude of MZM2. Here, the phase of the output of MZM2 is adjusted by controlling the bias point of Phase 2 in Fig. 1(a). The condition for canceling the first-order harmonics is that the following relation is satisfied:

\[ J_1\left(\frac{\pi A_2}{V_{\pi}}\right) = (1 - 2\gamma)J_1\left(\frac{\pi}{2}\right), \]

where \(J_n\) and \(\gamma\) are the \(n\)-th order Bessel function of the first kind and the splitting ratio of the MZMs, respectively. MZM3 is used to suppress the fourth-order harmonics. MZM3 is biased at the top point and is driven with frequency \(2f_s\), which is generated by a frequency doubler. The optical spectrum of the output of MZM3 is shown in Fig. 1(d). The driving amplitude and the phase of MZM3 is
adjusted so that the fourth-order harmonics of MZM1 are canceled. The condition is that the following relation is satisfied:

$$J_2\left(\frac{\pi A_3}{V_\pi}\right) = J_4\left(\frac{\pi}{2}\right)$$  \hspace{1cm} (6)

Finally, we use MZM4 to suppress the unwanted carrier component generated by MZM1, MZM2, and MZM3. Fig. 1(e) shows the optical spectrum of the output of MZM4. The intensity and the phase are controlled by adjusting the bias voltage of MZM4 and Phase 4. The outputs of MZM1, MZM2, MZM3, and MZM4 are polarization multiplexed as x- and y-polarization components by a polarization beam combiner (PBC) after the polarization rotation section in the DP-QPSK modulator, and added together into a linearly polarized optical signal using a polarizer. A frequency-quadruple two-tone lightwave signal is generated, suppressing the first- and fourth-order harmonics and the carrier components, as shown in Fig. 1(f). Here, it should be noted that we can use a commercially available DP-QPSK modulator and a frequency doubler. Usually, the RF amplitude needed for the $2f_s$ signal is much smaller than $V_\pi$, because the fourth-order harmonics component is about 20-dB smaller than the required two-tone signal. Therefore, an expensive modulator and frequency doubler with wideband frequency characteristics are not required in our proposed method.

### 3 System setup

The numerical simulation and the experiment was performed using the system setup shown in Fig. 2. In the figure, we omitted bias-controll electric lines for simplicity. A lightwave with a wavelength of 1549.5 nm (193.47 THz) was modulated by a X-cut DP-QPSK modulator. The modulator had a polarizer at the input so that only TE-polarized lightwaves were fed to the four MZMs through the power splitters in that. The lightwave from the LD was polarization-controlled (PC) to maximize the optical output power of the modulator. The lightwaves from the MZMs were added together as described above, MZM1 and MZM2 were driven by 10 GHz RF signals. MZM3 was driven by a 20 GHz RF signal generated by a frequency doubler. The phases of the RF signals for MZM2 and MZM3 were controlled using RF phase shifters (PSs). Attenuators (ATTs) were used for adjusting the amplitudes of the driving RF signals. The driving RF amplitudes for the DP-QPSK modulator and bias points were adjusted while observing the output.
optical spectrum using an optical spectrum analyzer (OSA; Anritsu, MS9710C, 0.05 nm resolution). The extinction ratio of the MZMs was assumed to be 20 dB in the simulation.

4 Results and discussion

First, we performed a numerical simulation to investigate the ideal performance of our proposed scheme. Fig. 3(a) and (b) show the results of the numerical simulation. Fig. 3(a) is the optical spectrum when only MZM1 was used. Among the many harmonics, the second-order harmonics component is needed to realize the

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

Fig. 3. Optical spectra of output lightwaves and suppression of unwanted high-order harmonics and carrier components.
quadruple-frequency two-tone signal. Fig. 3(b) is the optical spectrum when all the MZMs were active. In the numerical simulation, we could completely cancel the first- and fourth-order harmonics and the carrier components at the same time, as shown in Fig. 3(b). Figs. 3(c) and (d) show the results of the experiment. Fig. 3(c) is the optical spectrum when only MZM1 was used. The power level of the fourth-order harmonics was about 20.5 dB smaller than the required two-tone signal. The carrier component was larger than that in the simulation. This may have been caused by the carrier power from MZM2, MZM3, and MZM4, which were not modulated. When MZM1, MZM2, MZM3 and MZM4 were all used, the power levels of the fourth-order harmonics and carrier components were respectively suppressed to levels 36.8 dB and 40.3 dB smaller than the two-tone signal, as shown in Fig. 3(d). The power level of the first-order harmonics was also suppressed. However, we could not evaluate the suppression because of the inadequate resolution of our optical spectrum analyzer. We also evaluated the suppression ratio of the unwanted components against fluctuations of the amplitude of the RF signal $A_n$ and bias voltages $V_{bias}$ for the MZMs by numerical simulation. Fig. 3(e) shows the suppression ratio of the unwanted components against the amplitude fluctuation $\Delta A_n$ which is normalized by $V_\pi$. The suppression ratio was calculated by changing the fluctuation of one parameter, keeping the other amplitude and bias voltage at the optimum. Even when we adjusted all the parameters to optimum, the suppression ratio was limited by the unwanted third-order harmonics which is not suppressed in our proposed scheme. When we change the amplitude $A_3$ for MZM3, the characteristic curve became bilaterally asymmetric. This is because the $A_3/V_\pi$ is as small as 0.11 $V_\pi$. Therefore, when $A_3$ is decreased, the change of the suppression is soon saturated. To assure the suppression ratio of less than $-20$ dB, the amplitude fluctuation $\Delta A_n/V_\pi$ has to be controlled to less than about 0.03 $V_\pi$. Fig. 3(f) shows the suppression ratio against the fluctuation of bias voltages for MZMs. To assure the suppression ratio of less than $-20$ dB, the bias fluctuation $\Delta V_{bias}/V_\pi$ has to be also controlled to less than about 0.03 $V_\pi$. These adjustments of the amplitude and the bias can be controlled by using commercially available stabilizers for MZMs.

5 Conclusion

We studied a novel method for generating a two-tone lightwave signal, in which the first- and fourth-order harmonics and the carrier components are suppressed using a DP-QPSK modulator. The performance was investigated by numerical simulation and an experiment. The simulation results clearly showed that the proposed scheme works according to the theory. In the experiment, a quadruple-frequency two-tone signal was successfully generated, and the power level of the unwanted components was suppressed.