Full-duty triangular pulse generation based on a polarization-multiplexing dual-drive Mach-Zehnder modulator

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Abstract: A simple and flexible photonic approach to generating a triangular microwave waveform using a single integrated polarization-multiplexing dual-drive Mach-Zehnder modulator (PM-DMZM) and a polarizer is proposed and demonstrated, which needs no specific large modulation indices or an optical filter. In the proposed method, one sub-Mach-Zehnder modulator (MZM) in the PM-DMZM is driven by a fundamental frequency, which generates an optical signal composed of an optical carrier and a +1st-order sideband along one polarization direction; and the other sub-MZM is driven by a frequency tripled signal, generating an optical carrier and a −1st-order sideband along the orthogonal polarization direction. By adjusting the polarization direction of the polarizer following the PM-DMZM, which changes the power ratio of the two sidebands, optical intensity with expression corresponding to the Fourier expansion of a triangular-shaped waveform is obtained. Different from the previously reported approaches, neither specific large modulation index nor optical filtering is required, which guarantees a large operational frequency range and improved robustness. A proof-of-concept experiment is carried out. 5-GHz triangular-shaped waveform signals are successfully generated with different modulation indices.

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References and links
1. Introduction

Due to its potential application in all-optical signal processing systems [1–3], triangular waveform generation based on photonic technologies has been widely studied recently. Various approaches have been proposed [4–17]. One typical method is implemented based on frequency-to-time mapping (FTTM) [4,5], where the optical spectrum is shaped to have a triangular envelope, and then converted to a temporal triangular waveform. Line-by-line manipulation of the optical spectral comb [6] or self-convolution of a rectangular-shaped pulse [7] were also reported to generate the triangular waveform. These schemes, however, can only generate a triangular pulse with a small duty cycle (<1) [4–7]. In order to produce triangular pulses with a large or even full duty cycle, external modulation of a continuous wave (CW) optical carrier was proposed [8–17]. The key of this kind of approach is to control the frequency components of the generated signal to have amplitudes that are approximately equal to the Fourier components of a triangular waveform. Since the triangular waveform has only the odd-order harmonics of its repetition rate with amplitude ratios of exactly 1/k^2 (k is the harmonic order), external modulation with a specific modulation index and/or optical filters following the external modulator are always needed to guarantee the amplitude ratios among different frequency components [8–12], which not only results in complicated configurations, but also limits the frequency tunability and robustness. In order to avoid the use of optical filters, methods that utilize a dual-electrode Mach Zehnder modulator (DE-MZM) followed by a dispersion device [13], a DPMZM with a 90° electrical hybrid coupler [14], and a DPMZM driven by two RF signals with different frequencies (f and 3f) [15] are proposed. But a specific modulation index is still needed [13,14], or the modulation indices of the two sub-MZMs need to have a specific relationship [15]. In addition, triangular waveforms can be generated by introducing an optoelectronic oscillator to avoid the use of an external microwave source [16,17], but the above limitations still exist.

In this paper, we propose and experimentally demonstrate a photonic approach to generating a triangular microwave waveform using a single integrated polarization-multiplexing dual-drive Mach-Zehnder modulator (PM-DMZM) and a polarizer. Compared to the previously reported approaches, the proposed scheme generates triangular waveforms by simply adjusting the polarization direction of the polarizer following the PM-DMZM to obtain the required amplitude ratios among the frequency harmonics. Neither an optical filter nor a specific modulation index is required. An experiment is carried out. 5-GHz triangular-shaped waveform signals are successfully generated for different modulation indices conditions.

2. Principle

The schematic of the proposed triangular microwave waveform generation based on a PM-DMZM and a polarizer is shown in Fig. 1. A lightwave with an angular frequency of ω_0 generated by a laser diode (LD) is sent to the PM-DMZM, and then split into two parts with equal powers. In the upper branch, a RF signal with a frequency of ω_m and an amplitude of V_i
is divided into two parts with equal powers and a phase difference of $\theta_1$, which are then introduced to the two RF ports of sub-DMZM1, respectively. The bias of sub-DMZM1 is set to be $V_{bias1}$. The optical field at the output of sub-DMZM1 can be written as

$$E_i(t) \approx E_0 e^{i\omega t} \left[ e^{i\beta \cos (\omega t + \phi)} + e^{i\beta \cos (\omega t)} \cdot e^{i\phi} \right]$$

(1)

where $E_0$ is the amplitude of the optical carrier, $\beta = \left( \sqrt{2} \pi V_{bias1} / (2V_{z1}) \right)$, $\phi_1 = \pi V_{bias1} / V_{z1}$, $V_{z1}$ is the half-wave voltage of sub-DMZM1. Considering small-signal modulation condition, by applying the Jacobi-Anger expansion to Eq. (1), we have

$$E_i(t) \approx E_0 J_0(\beta_1) e^{i\omega t} \left[ 1 + e^{i\phi} \right] + jE_0 J_1(\beta_1) e^{i\omega t} e^{i\phi} \left[ e^{i(\phi + \phi_1)} + 1 \right]$$

(2)

where $J_n$ is the $n$th-order Bessel function of the first kind. It can be seen that when $\theta_1 + \phi = \pi$ (or $\theta_1 + \phi_1 = \pi$), optical single sideband (OSSB) modulation with −1st-order (or + 1st-order) sideband suppressed will be implemented [18]. By adjusting $\theta_1$ and $\phi_1$ to realize OSSB with + 1st-order sideband suppressed in sub-DMZM1, the corresponding output optical filed will be as follows

$$E_i(t) \approx 2 \cos(\phi / 2) E_0 J_0(\beta_1) e^{i\omega t} + j \sin \phi_1 E_0 J_1(\beta_1) e^{i\omega t}$$

(3)

In the lower branch, a RF signal with frequency of $3\omega_m$ and an amplitude of $V_2$ is divided into two parts with equal powers and a phase difference of $\theta_2$, which are introduced to the two RF ports of sub-DMZM2. By adjusting $\theta_2$ and $\phi_2$ to realize OSSB with −1st-order sideband suppressed in sub-DMZM2, the output optical field will be

$$E_2(t) \approx 2 \cos(\phi_2 / 2) E_0 J_0(\beta_2) e^{i\omega t} \cdot \frac{\phi}{2} - j \sin \phi_2 E_0 J_1(\beta_2) e^{i\omega t} \cdot j \phi$$

(4)

where $\beta_2 = \left( \sqrt{2} \pi V_{bias2} / (2V_{z2}) \right)$, $\phi_2 = \pi V_{bias2} / V_{z2}$, $V_{bias2}$ and $V_{z2}$ are the DC bias and the half-wave voltage of sub-DMZM2, respectively, and $\phi$ is the phase difference between the modulated RF signals in the lower and the upper branches.

Fig. 1. (a) Schematic of the proposed triangular microwave waveform generator based on a single PM-DMZM and a polarizer; (b) the working principles. LD: laser diode; PC: polarization controller; DMZM: dual-drive Mach-Zehnder modulator; PM-DMZM: polarization-multiplexing dual-drive Mach-Zehnder modulator; PR: polarization rotator; PBS: polarization beam splitter; PD: photodetector. Pol: polarizer.
Due to the 90° polarization rotator, the polarization states of the two sub-DMZMs’ outputs are orthogonal. The two orthogonally polarized lightwaves are combined at the output of the PM-DMZM and sent to a polarizer with its polarization direction of an angle $\phi_0$ to one of the polarization axes, with the output optical field as follows

$$E(t) = E_1(t) \cos \alpha + E_2(t) \sin \alpha$$  \hspace{1cm} (5)

By introducing the signal in Eq. (5) into the PD for square-law detection, the AC term of the output current can be written as

$$i_0(t) \propto \left[ J_0(\beta_1) J_1(\beta_1) \cos(\phi_0 / 2) \sin \phi_1 \cos^2 \alpha \cos(\omega_m t + \phi_1 / 2 + \pi) \\
+ J_0(\beta_2) J_1(\beta_2) \cos(\phi_0 / 2) \sin \phi_2 \sin \phi_1 \cos \alpha \cos \alpha \cos(\omega_m t + \phi_2 / 2 + \pi + \phi) \\
+ J_1(\beta_1) J_1(\beta_1) \sin \phi_1 \sin \phi_2 \sin \alpha \cos \alpha \cos(4 \omega_m t + \phi) \right]$$  \hspace{1cm} (6)

When $\phi_1 = \phi_2 = \phi_1 - \phi_2$ are satisfied, Eq. (6) can be simplified as

$$i_0(t) \propto \left[ J_0(\beta_1) \cos \alpha + J_1(\beta_1) \sin \alpha \right] \cos(\phi_0 / 2) \sin \phi_1 \cos \alpha \cos(\omega_m t + \phi_1 / 2 + \pi) \\
+ \left[ J_0(\beta_2) \cos \alpha + J_1(\beta_2) \sin \alpha \right] \cos(\phi_0 / 2) \sin \phi_2 \sin \alpha \cos \alpha \cos(3 \omega_m t + \phi_1 / 2 + \pi + \phi) \\
+ J_1(\beta_1) J_1(\beta_2) \sin^2 \phi_1 \sin \alpha \cos \alpha \cos(4 \omega_m t + 2 \phi)$$  \hspace{1cm} (7)

Since once $\phi_1$ and $\phi_2$ is set, $\phi$ will also be a certain value for different RF frequency values of $\omega_m$. Thus the large working range of the system can be ensured. It is well known that a Fourier expansion of typical triangular waveform is given by

$$T(t) \propto \cos \omega t + \frac{1}{9} \cos 3 \omega t + \frac{1}{25} \cos 5 \omega t + \cdots$$  \hspace{1cm} (8)

When the following equations are satisfied

$$\left[ J_1(\beta_1) \cos \alpha \right] / \left[ J_0(\beta_1) \sin \alpha \right] = 9$$
$$J_1(\beta_1) \sin \phi \cos \alpha \right] \left[ J_0(\beta_1) \cos \alpha + J_1(\beta_1) \sin \alpha \right] \cos(\phi / 2)$$  \hspace{1cm} (9)

harmonics higher than the 3rd-order will be neglected, and Eq. (7) can be simply considered as Eq. (8). Note that there is always a certain value of $\alpha$ to meet the 1/9 magnitude relationship between the 1st- and 3rd-order harmonics in Eq. (7) for arbitrary $\beta_1$ and $\beta_2$, and a wide range of $\beta_1$ and $\beta_2$ values can satisfy the requirement to effectively suppress the 4th-order harmonics, thus a fixed modulation index is not required. In addition, no optical filter is needed, which avoids the limitation with the working frequency range of the system.

3. Experimental results and discussions

An experiment based on the setup shown in Fig. 1 is carried out. A CW light at 1550 nm from the LD (TeraXion NLL04) is sent to the PM-DMZM (Fujitsu FTM7980EDA). The PM-DMZM has a 3-dB bandwidth of 20 GHz and a half-wave voltage of 3.5 V. The modulated microwave signals are generated by a microwave signal generator (Keysight N5183B). The PD (XPDV2120-RA-VF-FP) has a bandwidth of 40 GHz and a responsivity of 0.65 A/W. The waveforms are observed by a sampling oscilloscope (Agilent 86100C). The optical spectra and the electrical spectra are observed by an optical spectrum analyzer (OSA, Yokogawa AQ6370C) with a resolution of 0.02 nm, and an electrical spectrum analyzer (ESA, R&SFSV40), respectively.
By injecting a 2-dBm 5-GHz RF signal and an 11-dBm 15-GHz RF signal to the two sub-DMZMs, respectively, the modulation index values are calculated to be $\beta_1 = 0.25$, $\beta_2 = 0.71$, respectively. The optical spectrum at the output of the PM-DMZM is shown in Fig. 2(a). Three main components exist in the spectrum, with frequency distance of 15 GHz and 5 GHz, respectively. To verify that the two sidebands are along two orthogonal polarization axes, a PBS is connected to the output of the PC following the PM-DMZM. The optical spectra at the two output ports of the PBS are shown in Figs. 2(b) and 2(c), respectively. It can be seen that two orthogonal OSSB signals with a respective upper and lower sideband exist, which agrees well with the analyses.

By adjusting the PC to adjust the polarization direction $\alpha$ of the polarizer, optical intensity with expression corresponding to the first two-term Fourier expansion of a triangular-shaped waveform is obtained and a triangular waveform is generated. The electrical spectrum and the generated waveform are shown in Figs. 3(a) and 3(b), respectively. As shown in the electrical
spectrum in Fig. 3(a), the 3rd harmonics at 15 GHz is 19.1 dB lower than the fundamental component at 5 GHz. The value is close to the ideal value of 19.08 dB, corresponding to the amplitude ratio of 9 of the first two-term Fourier expansion of a triangular waveform. The even order harmonics (2nd and 4th) are suppressed by more than 29 dB, which can be ignored [13]. The eye diagram of the observed waveform and the corresponding ideal triangular waveform are shown in Fig. 3(b), and the root mean square error (RMSE) between the measured waveform and the ideal one is 3.21e-3. Thus it can be seen that the measured waveform fits well with the ideal one.

As analyzed in Section 2, a wide range of $\beta_1$ and $\beta_2$ values can satisfy the requirement of the scheme and a fixed modulation index is not required. In the experiment, another group of modulation indices are chosen to prove this. The modulation index values at the two sub-MZMs are tuned to be $\beta_1 = 0.44$, $\beta_2 = 0.53$, respectively. By carefully adjusting the PC, the observed electrical spectrum and the generated waveform are shown in Figs. 4(a) and 4(b), respectively. A triangular waveform is successfully generated. The 3rd harmonics at 15 GHz is 19.01 dB lower than the fundamental component at 5 GHz, being very close to the ideal value of 19.08 dB. The even order harmonics (2nd and 4th) are suppressed by more than 41 dB to be low enough. And the observed waveform also fits well with the ideal one, with the corresponding RMSE value of 1.98e-3. Thus it can be concluded that no fixed modulation index is needed, which greatly increases the system flexibility.

![Fig. 4. (a) Electrical power spectra of the generated triangular when $\beta_1 = 0.44, \beta_2 = 0.53$; (b) the eye diagram of the measured triangular waveform and the ideal one.](image)

By using the proposed scheme, a triangular-waveform generator is realized with no need of a fixed modulation index or an optical filter by using a single PM-DMZM and a polarizer. The stability of the system can be further improved by using a DC bias controlling circuit to avoid the DC bias drift problem. In addition, the system performance can be further improved if the RF power splitters and phase shifts can be adjusting more accurately. Since the scheme will work well with fixed phase shift values of $\phi_1$, $\phi_2$ and $\phi$ (such as $\pi/2$, $\pi/2$, $\pi$), thus by integrating the RF power splitters and phase shifts in the modulator, the structure will be made simpler with improved performance.

4. Conclusion

We proposed and demonstrated a photonic approach to generating a full-duty triangular waveform using a PM-DMZM and a polarizer. The proposed scheme has a compact structure,
requiring only one LD, one modulator, one polarizer and one PD. An optical signal composed of two orthogonal OSSB modulated signals is realized and the triangular waveform is generated by simply adjusting the polarization direction of the polarizer, which insures simple operation. Neither an optical filter nor a special modulation index is required, which guarantees the flexibility of the system. 5-GHz triangular-shaped waveform signals are successfully generated for different modulation indices conditions, where electrical spectra corresponding to the Fourier expansion of a triangular-shaped waveform are clearly observed, and the obtained waveforms fit well with the ideal ones. This program can find applications in all-optical signal processing systems.

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