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A simple photonic method to generate square and triangular microwave waveforms

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ABSTRACT

We report a simple photonic method to generate square and triangular microwave waveforms. Previous works normally need complicated processing of optical signals for the generation of these waveforms. Actually we find that the simplest microwave photonic link can do the same thing without any optical signal processing which is the key advantage of our method compared with previous works. The proposed signal generator only consists of a sinusoidal radio-frequency (RF) source, a conventional Mach–Zehnder modulator (MZM), and a photodetector (PD). The intensity modulated optical signal is directly coupled to a PD for square-law detection without any signal processing. By properly setting the modulation index of the MZM to 1.15 rad, a square waveform can be easily obtained. For triangular waveform generation, a 90° hybrid coupler is attached after PD to compensate the phase mismatch. Besides, neither optical nor electrical filters are needed in our link which can ensure a wide frequency range. The proposed scheme is theoretically analyzed and experimentally verified. Square and triangular waveforms at repetition rates of 3, 4, and 5 GHz are successfully generated.

1. Introduction

In recent years, photonic generation of arbitrary waveforms has been a hot topic due to its wide applications in radars, wireless communications and microwave signal process [1–4]. Among various signal profiles, square and triangular waveforms play important roles in optical frequency conversion, pulse compression and signal copy [5–7]. Various photonic approaches have been reported to generate square or triangular microwave waveforms. For example, square and triangular microwave waveforms can be generated based on optical spectrum shaping combined with frequency-to-time mapping [8–11]. An ultra-short optical pulse is shaped in frequency domain by an optical spectrum shaper with square or triangular shape. By frequency-to-time mapping in a dispersive element, square or triangular microwave waveforms can be generated. However, this method is lack of flexibility because of the fixed spectral response of an optical spectrum shaper. Besides, the generated microwave waveforms usually have small duty cycle (normally less than 1) which limits the applications of these waveforms. A promising method to generate full-duty-cycle (equal to 1) square and triangular microwave waveforms is external modulation [12–17]. For instance, square waveform can be generated using a dual-parallel Mach–Zehnder modulator (DPMZM) with a tunable bandpass filter [12] or a DPMZM by adjusting five direct current (DC) biases and radio frequency (RF) modulation index [13]. However, complicated and accurate DC bias control is required. Recently, a full-duty-cycle triangular waveform has been generated based on a microwave photonic filter with negative coefficient [14] or through the stimulated Brillouin scattering (SBS) in optical fiber [15]. But the repetition rate of the generated microwave waveform is difficult to tune. Besides, square and triangular microwave waveforms can be generated based on signal processing or pulse superposition in time-domain [16,17]. Moreover, two polarization-dependent MZMs or a polarization modulator (PolM) incorporated in a Sagnac loop have been reported to generate square and triangular waveforms [18,19]. The signal synthesis in the optical domain requires more modulators and optical processing elements [16–19], which increase the complexity of the signal generator.

It is worth noting that previous works normally require a complicated processing of optical signals for the generation of these waveforms, such as dispersion induced power fading in dispersive element with optical filter [8–11], complicated optical modulator [12,13], microwave photonic filter [14], SBS in optical fiber [15], signal process and pulse superposition in time-domain [16,17], polarization-dependent modulators [18], Sagnac loop [19], and polarization rotation effect in nonlinear optical fiber [20]. The extra optical signal processing makes the system costly, huge, and complicated.

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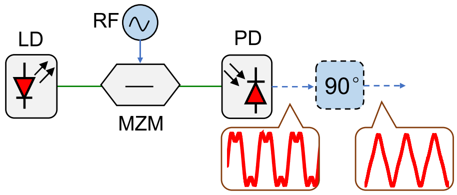

Fig. 1. Schematic diagram of the proposed signal generator. LD: laser diode, MZM: Mach–Zehnder modulator, RF: radio frequency, PD: photodetector, 90°: 90° hybrid coupler.

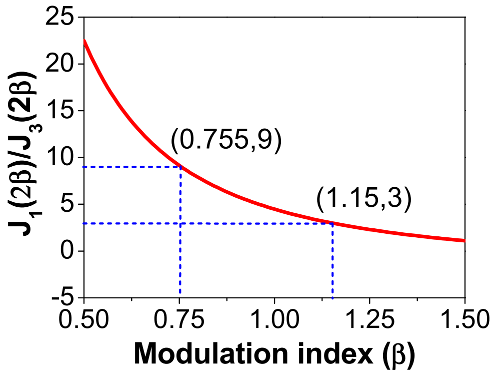

Fig. 2. The calculated value of $J_1(2\beta)/J_3(2\beta)$ versus the modulation index β.

In this letter, we propose a simple photonic method to generate square and triangular waveforms using the simplest microwave photonic link without any optical signal processing procedure. The link only has a sinusoidal RF source, a conventional Mach–Zehnder modulator (MZM), and a photodetector (PD). A square waveform can be directly generated by properly setting the RF power driven to the MZM. By attaching a 90° hybrid coupler to the PD, a triangular waveform can also be generated by synthetizing the signals in the electrical domain. Moreover, neither optical nor electrical filters are needed in our link which can ensure a wide frequency range. Square and triangular waveforms at repetition rates of 3, 4, and 5 GHz are experimentally generated. They agree well with the simulated results.

2. Principle of operation

The experimental setup of the photonic generation of square and triangular waveform is shown in Fig. 1. An optical carrier is coupled to a conventional single-drive MZM. The optical field at the output of MZM is

$$\begin{aligned} E(t) &= \frac{1}{2}E_0 e^{j\omega_0 t}\cdot\{e^{j[\beta\cos(\omega_m t)+\frac{\varphi}{2}]}+e^{-j[\beta\cos(\omega_m t)+\frac{\varphi}{2}]}\} \\ &= E_0 e^{j\omega_0 t}\cos(\beta\cos(\omega_m t)+\frac{\varphi}{2}) \end{aligned}, \qquad (1)$$

where E_0 and ω_0 are the amplitude and angular frequency of the optical carrier, V_{m} and ω_{m} are the amplitude and angular frequency of the RF signal, V_π and V_{DC} are the half-wave voltage and DC bias of the MZM, $\beta = \pi V_{\mathrm{m}}/V_\pi$ is the RF modulation index of the MZM, $\varphi = \pi V_{\mathrm{DC}}/V_\pi$ is the phase difference between the two arms of the MZM which is introduced by the DC bias.

When the modulated optical signal is detected by a PD for square-law detection, the photocurrent can be expressed as

$$\begin{aligned} i(t) &= E(t)\cdot E(t)^* \\ &= E_0^2\cos^2(\beta\cos(\omega_m t)+\frac{\varphi}{2}) \\ &= \frac{1}{2}E_0^2[\cos(2\beta\cos(\omega_m t)+\varphi)+1] \\ &= \frac{1}{2}E_0^2+\frac{1}{2}E_0^2\cdot[\cos(2\beta\cos(\omega_m t))\cos(\varphi)-\sin(2\beta\cos(\omega_m t))\sin(\varphi)] \end{aligned}. \qquad (2)$$

It is known that square and triangular waveforms can be expressed as Fourier expansion. It has been demonstrated that two Fourier components can make a good approximation of square and triangular waveforms because the power of higher-order harmonics decrease drastically [19]. Thus, square waveform and triangular waveform can be given by

$$S_q(t) \propto A-\cos(\Omega t+\theta)+\frac{1}{3}\cos(3\Omega t+3\theta), \qquad (3)$$

$$T_{ri}(t) \propto A+\cos(\Omega t+\theta)+\frac{1}{9}\cos(3\Omega t+3\theta), \qquad (4)$$

respectively, where A is a DC signal, Ω and θ are the repetition rate and phase of the square waveform and triangular waveform. From (3) and (4), it can be seen that the square and triangular waveforms consist of only odd-order harmonics. The MZM is biased at quadrature point (i.e. $\varphi = \pi/2$), Eq. (2) can be simplified as

$$\begin{aligned} i(t) &= \frac{1}{2}E_0^2-\frac{1}{2}E_0^2\sin(2\beta\cos(\omega_m t)) \\ &= \frac{1}{2}E_0^2+\frac{1}{2}E_0^2\cdot 2\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(2\beta)\cos[(2n-1)\omega_m t] \\ &= \frac{1}{2}E_0^2-E_0^2 J_1(2\beta)\cos(\omega_m t)+E_0^2 J_3(2\beta)\cos(3\omega_m t), \end{aligned} \qquad (5)$$

where J_1 and J_3 are the first- and third-order Bessel function of the first kind.

Fig. 2 shows the calculated value of $J_1(2\beta)/J_3(2\beta)$ versus the modulation index β. For the generation of square waveform, $J_1(2\beta)/J_3(2\beta)$=3 is required, thus, the modulation index of the MZM is calculated to be 1.15 rad. Comparing Eq. (3) with Eq. (5), the amplitude and phase requirement for the generation of square waveform are both satisfied.

On the other hand, the amplitude requirement for the generation of a triangular waveform needs $J_1(2\beta)/J_3(2\beta)$=9, thus, we have $\beta = 0.755$ rad. However, comparing Eq. (4) with Eq. (5), the phase relationship between the fundamental tone and the third-order harmonic is mismatched for the triangular waveform generation. To compensate for the phase mismatch, a broadband 90° hybrid coupler is attached after the PD. The photocurrent at the output of the 90° hybrid coupler is given by

$$i(t) = \frac{1}{2}E_0^2+E_0^2 J_1(2\beta)\cos(\omega_m t-\frac{\pi}{2})+E_0^2 J_3(2\beta)\cos(3\omega_m t-\frac{3\pi}{2}). \qquad (6)$$

Now, the amplitude and phase requirement for the generation of triangular waveform is fully satisfied. In addition, the repetition rate of the generated square and triangular microwave waveforms can be easily tuned by changing the frequency of the input sinusoidal RF signal. It is worth noting that, no optical signal processing procedure is required in our scheme. This is the key advantage of our method compared with previous works.

3. Experiment

A proof-of-concept experiment based on the setup shown in Fig. 1 was carried out to verify the proposed scheme. An optical carrier centered at 1550 nm was coupled to a conventional MZM with 3-dB bandwidth of 40 GHz and a half-wave voltage of 3.5 V. A sinusoidal RF signal from a microwave source is fed to the MZM which was biased at quadrature point to modulate the optical carrier. A PD with 3-dB bandwidth of 18 GHz was used to detect the modulated optical signal directly to generate square microwave waveforms. In order to obtain triangular microwave waveform, a broadband 90° hybrid coupler with 3-dB bandwidth of 18 GHz was added after PD. An optical spectrum analyzer (OSA) with resolution of 0.01 nm was used to record the modulated optical signal. An electrical spectrum analyzer (ESA) and an oscilloscope (OSC) were used to measure the electrical spectra and temporal waveforms of the generated square and triangular microwave waveforms, respectively.