Symmetry-Tunable Full-Duty Triangular-Shaped Waveform Generation Using a Simple Single-Drive Mach-Zehnder Modulator

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***Abstract*—A novel and simple photonic approach for generating symmetry-tunable full-duty triangular-shaped microwave waveforms is proposed and experimentally demonstrated. In this approach, a simple commercial single-drive Mach-Zehnder modulator (MZM) is adopted and driven by the radio frequency (RF) input. By properly presetting the RF modulation index and simply adjusting the direct current (DC) bias voltage of MZM, the full-duty triangular-shaped microwave waveforms with self-defined symmetrical coefficients can be obtained. A complete theoretical analysis on operation principle is presented and a proof-of-concept experiment is carried out. The full-duty triangular-shaped waveforms with tunable symmetrical coefficients at the repetition rate of 5 GHz are successfully generated. This approach features simple architecture, less variables, excellent reconfigurability and integrable capability, which are highly desired for the high-performance triangular-shaped waveform generator.**

***Index Terms*—Microwave photonics, triangular-shaped waveform, Mach-Zehnder modulator (MZM).**

I. Introduction

HIGH-SPEED triangular-shaped waveforms have been extensively investigated due to their wide applications in all-optical data processing [1], [2], optical wavelength conversion [3], pulse compression and signal copy [4]. Benefitting from the huge bandwidth, low loss and the immunity to electromagnetic interference, photonic generation of triangular-shaped waveforms is widely expected to overcome the bandwidth limitation in electrical solutions. In recent years, numerous triangular-shaped waveform generation schemes based on photonic techniques or devices have been proposed and demonstrated, such as optical spectral processing and frequency-to-time mapping (FTTM) [5], Fourier synthesis method [6], optical external modulation [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], and so on. In both FTTM and Fourier synthesis method, the high-precise pulse spectral processor is required to manipulate the harmonics of spectral comb lines or the spectral envelope of customized optical signals, which makes the system complicated and costly. In comparison, the optical external modulation, which avoids the pulse spectrum processing and combines the merits of better system stability, higher integrable capability offered by the commercial electrooptic modulators, can be considered as a promising solution to generate the desired triangular-shaped waveforms. Till now, kinds of triangular-shaped waveform generation approaches based on external modulation have been reported [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17]. For instance, the triangular-shaped microwave waveforms can be generated by using a phase modulator (PM) combined with an optical band-pass filter [7], which is employed to filter out the undesired optical sidebands. The triangular waveforms can also be generated by an PM incorporated with a Sagnac loop and dispersive fiber [8], or a Mach-Zehnder modulator (MZM) with a tunable optical delay line (ODL) and balanced photodetection [9], both of dispersive fiber and tunable ODL are used to generate the desired phase shifts on different optical sidebands. In [10], the dual-parallel MZM (DP-MZM) has been adopted to generate frequency-doubled triangular-shaped waveforms by using an electrical frequency tripler. In [11], by cascading an MZM with a polarization modulator located inside a Sagnac loop, the triangular-shaped waveforms with the capability of anti-dispersion transmission can be generated. Moreover, the triangular-shaped waveforms can also be generated based on the optoelectronic oscillator (OEO) [12], the Simulated Brillouin scattering (SBS) effect of fiber [13], etc. However, the above schemes focus on the symmetrical triangular-shaped waveform generation, which highly limit the flexibility of generated waveforms.

Theoretically, the generation of a flexible asymmetric triangular-shaped waveform, especially the waveform with tunable symmetry, requires the summation of infinite harmonics of the driven RF signal in optical or electrical domain. Normally, extra techniques are required to manipulate the phase and power weights of each harmonic. The proposed asymmetric triangular-shaped waveform generation schemes include the method based on a push-pull MZM with a tunable ODL [14], the scheme using parallel MZM arrays with four tunable phase shifters (PS) [15], the scheme based on parallel MZMs working on different polarization states [16], and the scheme using an integrated I/Q (I: in-phase, Q: quadrature phase) modulator with a tunable PS [17]. All above schemes claimed that the symmetry-tunable full-duty triangular-shaped waveforms can be generated by the

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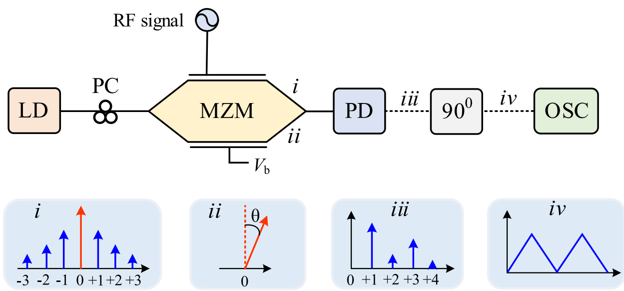

Fig. 1. Schematic diagram of the proposed symmetry-tunable full-duty triangular-shaped waveform generator. LD, laser diode; MZM, Mach-Zehnder modulator; PC, polarization controller; PD, photo-detector; 90°, 90-degree microwave phase shifter; OSC, oscilloscope. Spectra of optical signal in the upper arm (*i*) and the lower arm (*ii*) of the modulator. Frequency spectrum of electrical signal after photo-detection (*iii*) and the time-domain waveform after 90-degree microwave phase-shifter (*iv*).

modulator arrays with the help of the tunable ODL, polarization controlling or the tunable RF PS. But only the scheme in [17] has been experimentally demonstrated. In [17], an integrated I/Q modulator is adopted and driven by two RF input branches with tunable phase shifting. By properly adjusting the tunable electrical PS and the three DC bias voltages of I/Q modulator as well as the RF modulation index values, this scheme can generate the triangular-shaped waveforms with the tunable symmetrical coefficients. However, the employment of the tunable electrical PS makes the system complicated and bandwidth limited. Moreover, simultaneously adjusting five variables (RF modulation index, phase shift of the electrical PS, three DC bias voltages) brings inconvenience for practical manipulation and significantly effects the system stability as well as the fidelity of the generated waveforms.

In this paper, a novel photonic approach for generating full-duty triangular-shaped microwave waveforms with tunable symmetry is proposed and experimentally demonstrated. A simple commercial single-drive MZM is adopted and driven by the RF input. By properly presetting the RF modulation index, the desired phase and power weight of each harmonic can be obtained by simply adjusting the DC bias voltage of MZM. Meanwhile, by phase shifting the detected output signals of modulator with a 90°-phase shifter, the full-duty triangular-shaped waveforms with self-defined symmetrical coefficients can be achieved. A complete theoretical analysis on operation principle is given and a proof-of-concept experiment is carried out. The full-duty triangular-shaped waveforms with tunable symmetry ($34\% < \delta < 66\%$) at repetition rate of 5 GHz are successfully generated, which validate the feasibility of this approach.

II. Principle

The schematic diagram of the proposed symmetry-tunable full-duty triangular-shaped waveforms generator is shown in Fig. 1. The lightwave emitted from the laser diode (LD) is modulated by the RF signal via a single-drive MZM. A polarization controller (PC) following LD is employed to align the polarization state of lightwave so as to minimize the polarization dependent loss. The RF signal is applied into one arm of MZM and the other arm of MZM is driven by the DC bias voltage. The modulated optical signals out of MZM are converted into its electronic counterparts by the photodetector (PD). Then the following 90-degree microwave phase shifter (MPS) introduces a static 90-degree phase shift into the detected signals. By properly presetting the modulation index of RF signal and simply adjusting the DC bias voltage of MZM, the desired full-duty triangular-shaped waveform with self-defined symmetrical coefficient can be obtained. The detailed optical spectrum in the upper arm of MZM is given in Fig. 1(i) and that in the lower arm is shown in Fig. 1(ii). Fig. 1(iii) and (iv) respectively present the frequency spectrum of the modulated signals after the photodetection and the time-domain waveform after the 90-degree phase shifter.

The optical fields at the input ($E_{\text{in}}(t)$) of MZM can be written as:

$$E_{\text{in}}(t) = E_0 \exp(j\omega_0 t) \tag{1}$$

where E_0 and ω_0 respectively denotes the amplitude and angular frequency of the optical carrier.

The output modulated optical fields ($E_{\text{out}}(t)$) of MZM can be given by:

$$E_{\text{out}}(t) = \sqrt{2}/2 \cdot E_{\text{in}}(t)\left\{\exp(jm\cos(\omega t)) + \exp(j\theta)\right\} \tag{2}$$

where ω denotes the angular frequency of input RF signal, m represents the RF modulation index and it is defined as $m = \pi V_{RF}/V_\pi$, V_{RF} denotes the amplitude value of RF signal and V_π is the half-wave voltage of employed MZM, θ denotes the phase shift introduced by the DC bias voltage and it can be expressed as $\theta = V_{\text{bias}}/V_\pi$.

According to the square law detection, the electrical signal ($I(t)$) converted from the modulated output signal of MZM can be expressed as

$$\begin{aligned} I(t) &\propto E_{\text{out}}(t) \times E^*_{\text{out}}(t) \\ &\propto |E_{\text{in}}(t)|^2/4 \cdot \left\{ \begin{array}{l} 1 + \cos(m\cos(\omega t))\cos(\theta) \\ + \sin(m\cos(\omega t))\sin(\theta) \end{array} \right\} \\ &\propto |E_{\text{in}}(t)|^2/4 \cdot \left\{ \begin{array}{l} 1 + \cos(\theta)\, J_0(m) \\ + 2\cos(\theta)\sum_{k=1}^{+\infty} \\ \quad (-1)^k J_{2k}(m)\cos(2k(\omega t)) \\ + 2\sin(\theta)\sum_{k=0}^{+\infty}(-1)^k J_{2k+1}(m) \\ \quad \cos((2k+1)(\omega t)) \end{array} \right\} \end{aligned} \tag{3}$$

where $J_n(\cdot)$ is the nth-order Bessel function of the first kind. To simplify the analysis, (3) can be further expressed as the sum of harmonics:

$$I(t) \propto |E_{\text{in}}(t)|^2/4 \cdot \left[1 + \cos(\theta)\, J_0(m) + \sum_{n=1}^{+\infty} a_n \cos(n\omega t)\right] \tag{4}$$

where

$$a_n = \begin{cases} 2(-1)^n \cos\theta J_n(m)\, n\, is\, even \\ 2(-1)^n \sin\theta J_n(m)\, n\, is\, odd \end{cases} \tag{5}$$

To generate the desired waveforms, the detected signals are then delivered into a 90-degree MPS, which introduces 90-degree phase shift for all harmonics, the output signal of MPS

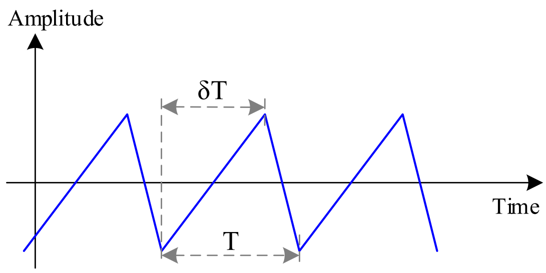

Fig. 2. The symmetrical coefficient versus the full-duty triangular-shaped waveform.

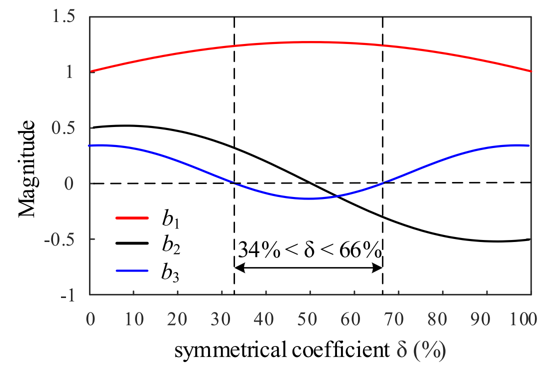

Fig. 3. Magnitude values of b_1, b_2 and b_3 versus symmetrical coefficient δ.

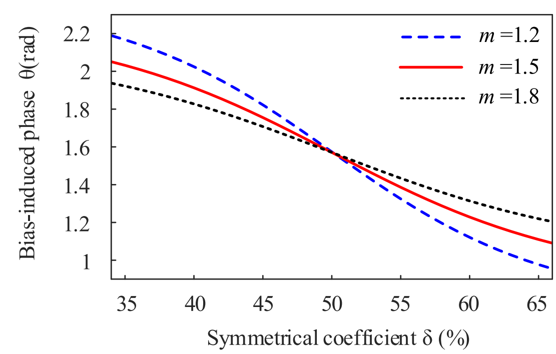

Fig. 4. The required bias phases θ under different RF modulation index m when $34 < \delta < 66\%$. (The modulation index varies from 1.2 to 1.5, 1.8).

can be written as:

$$I(t) \propto |E_{\text{in}}(t)|^2/4 \cdot \left\{1 + \cos(\theta) J_0(m) + \sum_{n=1}^{+\infty} [a_n \sin(n\omega t))]\right\} \quad (6)$$

As shown in (6), the generated waveform of the proposed scheme is built by a list of sinusoidal harmonics and the DC term. By properly adjusting the values of power weights (a_n) of each harmonic, the desired triangular-shaped waveforms can be obtained. Here we introduce the symmetrical coefficient δ of the triangular-shaped waveforms as the ratio of temporal rising edge to the entire repetition period, as shown in Fig. 2.

As discussed in [17], the asymmetrical triangular-shaped waveforms can be written as:

$$s(t) = \sum_{n=1}^{\infty} b_n \sin(n\omega t) \quad (7)$$

where b_n represents the magnitude of the n-th sinusoidal harmonic and it can also be expressed as

$$b_n = \omega/\pi \cdot \left[\begin{array}{l} \int_{-\delta T/2}^{\delta T/2} (t/\delta T) \sin(n\omega t)\, dt \\ + \int_{\delta T/2}^{T-\delta T/2} \{(T-2t)/[2T(1-\delta)]\} \sin(n\omega t)\, dt \end{array}\right] \quad (8)$$

As shown in (7), a flexible full-duty triangular-shaped waveform is built by infinite terms of sinusoidal harmonics. In order to achieve a flexible triangular-shaped waveform with desired symmetrical coefficient, approximation between $I(t)$ in (6) and $s(t)$ in (7) should be made. To reduce the system complexity, we only consider the first three terms in both equations. Thus, the following relationship should be satisfied:

$$a_1 : a_2 : a_3 = b_1 : b_2 : b_3 \quad (9)$$

For a full-duty triangular-shaped waveform with a self-defined symmetrical coefficient δ, the magnitudes b_1, b_2 and b_3 are solvable, their relationship is calculated and given in Fig. 3. Thus, to generate a desired flexible triangular-shaped waveform based on the proposed approach, the relationship between the bias phase shift θ and the RF modulation index m can be derived based on (6), (7) and (9), which can be written as:

$$\theta = \arctan\{[J_2(m)(b_1 + b_3)]/[[J_1(m) - J_3(m)]\, b_2]\} \quad (10)$$

Besides, according to (5), when $0 < \theta < \pi$, $a_1 = 2\sin\theta J_1(m)$ and $a_1 > 0$, $a_3 = -2\sin\theta J_3(m)$ and $a_3 < 0$, while $a_2 = -2\cos\theta J_2(m)$ and its corresponding values can be smaller or larger than 0. Similarly, when $\pi < \theta < 2\pi$, $a_1 < 0$, $a_2 \geq 0$ or $a_2 \leq 0$, $a_3 < 0$. As can be seen from Fig. 3, the ideal magnitude of first term b_1 should always be positive for the flexible full-duty triangular-shaped waveforms. Meanwhile, the waveform with full-scale asymmetrical coefficient requires that the magnitude of third term b_3 is smaller than 0 when $34\% < \delta < 66\%$ and its value is larger than or equal to 0 in case of other asymmetrical coefficient values. Therefore, the DC bias phase θ in proposed scheme should be set as $0 < \theta < \pi$, and the full-duty triangular-shaped microwave waveforms with the symmetrical coefficient $34 < \delta < 66\%$ can be generated by properly adjusting the DC bias voltage of MZM. Furthermore, the required DC bias phase value is calculated by the RF modulation index m , and their relationship is given by (10).

Furthermore, to realize the desired triangular-shaped waveform by generating the first three terms of its harmonics, the modulation index of RF input should satisfy $J_2(m) \neq 0$, which means that the second term must exist to adjust the symmetrical coefficient of the generated triangular-shaped waveform. Besides, the modulation index m in our proposal can be preset within a range of $1 \leq m \leq 2$. With a given m, the DC bias phase θ can be solved by (10). Fig. 4 shows the require bias phase θ versus symmetrical coefficient δ at three different modulation

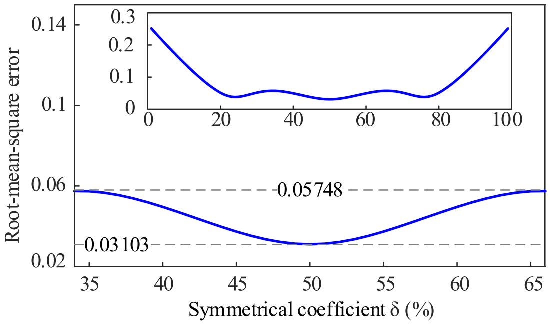

Fig. 5. Calculated root-mean-square error versus symmetrical coefficient with three terms of harmonic fitting.

index values. Note that two variables (modulation index, bias phase) are not fixed at a certain value, but with a series of solutions. As can be seen from Fig. 4, when m is set as 1.5, the θ should be aligned from 2.05 rad to 1.11 rad to obtain the triangular-shaped waveform with symmetrical coefficients from 34% to 66%. If we adjust the input power of RF signal, i.e., the modulation index m is preset as other values (1.2 or 1.8), the desired θ would be changed correspondingly.

In order to evaluate the approximation error of the generated waveforms in our proposal, we introduce the root-mean-square error (RMSE), which is defined as follows:

$$\eta = \sqrt{\left[\sum\nolimits_{k=1}^{N} (X_k - Y_k)^2\right] / N} \tag{11}$$

where X_k and Y_k represent the normalized amplitude value of the approximate waveform and the ideal triangular-shaped waveform respectively, and N represents the number of sampling points in a period of waveform. Normally, when the RMSE is small enough ($\eta \leq 7\%$), the generated waveform can be considered as desired. Fig. 5 illustrates the RMSE of the generated triangular-shaped waveforms with only three terms of harmonic fitting as the function of the symmetrical coefficients based on the proposed approach. As can be seen from Fig. 5, the generated waveform in our proposal has tolerable error of ($3.103\% \leq \eta \leq 5.748\%$) by simply adjusting only two variables (modulation index and DC bias) on a single MZM. Note that the approximate waveform can be the generated waveforms by simulations or the measured waveforms by experiments.

III. Results and Discussions

A proof-of-concept experiment based on the setup shown in Fig. 1 was carried out to verify the proposed approach. A continuous wave (CW) light centered at 1550 nm and the power of 13 dBm is emitted from a laser diode (LD, CBDX-NC-NC-NN-NN-FA). The light is then injected into a single dual-drive MZM (FTM7937EZ/202) by passing through a PC, which is properly adjusted to minimize the polarization dependent loss. The 3-dB bandwidth of MZM is 40 GHz and its half-wave voltage is about 5.5 V. An analog signal source (Ceyear 1435F) is used to generate the RF input signal with the center frequency of 5 GHz. The RF input drives one electrode of MZM and the other electrode is null driven. The output optical signal of MZM

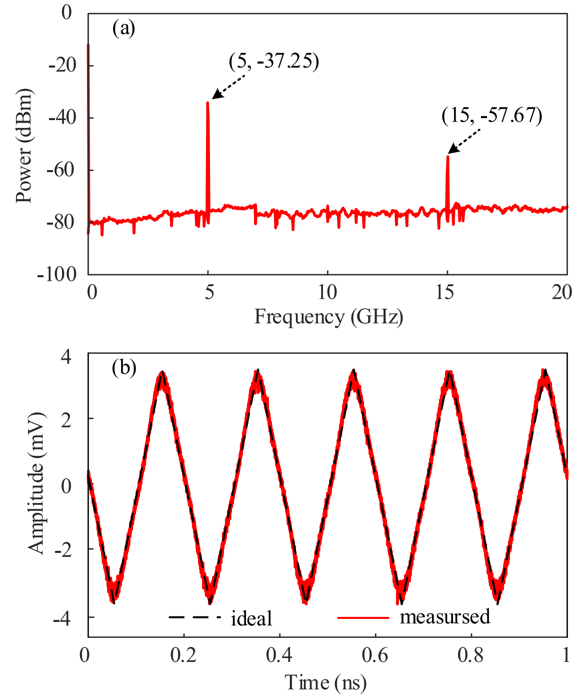

Fig. 6. Measured (a) electrical spectrum and (b) temporal waveform of the generated 5 GHz symmetrical triangular-shaped waveform.

is detected by a PD (KG-PT-20G-A-FA) with a 3-dB bandwidth of 20 GHz and a responsivity of 0.8 A/W. The electrical spectrum of the detected signal is obtained by using a 30 GHz electrical spectrum analyzer (FSV30) and the corresponding temporal waveform is captured by an oscilloscope (DCA-X 86100D) with bandwidth of 40 GHz. The following 90-degree microwave phase shifting of the detected signal is performed in an offline program.

We firstly investigate the generation of a symmetrical triangular-shaped waveform (i.e., the symmetrical coefficient is 50%) based on the proposed scheme. According to the discussion in Section II, if the RF modulation index is fixed, we can adjust the DC bias to obtain the symmetrical triangular waveform, i.e., the bias phase θ should be set as $\pi/2$ when the modulation index m is fixed as 1.5. In experiments, the output power of signal generator (SG) is fixed as 18.3 dBm and the DC bias voltage is set as 2.75 V. The measured electrical spectrum is shown in Fig. 6(a), which mainly consists of the fundamental tone at 5 GHz and the third-order harmonic of 15 GHz. The power values of the first- and third-order harmonic are -37.25 dBm and -57.67 dBm respectively. Obviously, their difference value is about 20.42 dB, which fits well with the theoretical value of 19.08 dB. Meanwhile, the second-order harmonic at 10 GHz has not been captured, whose influence on the obtained waveform can be neglected. Fig. 6(b) gives the obtained temporal waveform by phase shifting the recorded waveform by the OSC. As can be seen, a 5 GHz symmetrical triangular-shaped waveform has been successfully achieved. To evaluate the waveform approximation error, we calculated the RMSE of the captured waveform by comparing with the ideal triangular waveform. The RMSE between the obtained and

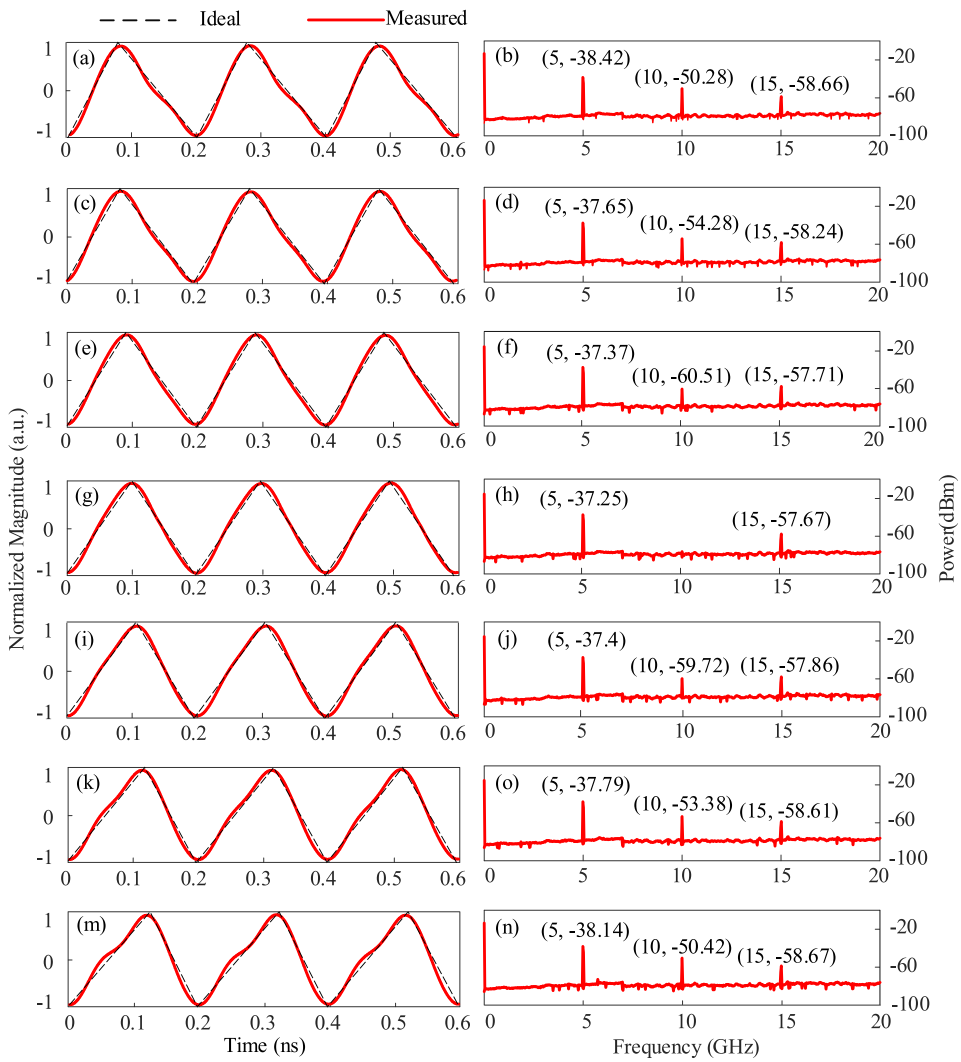

Fig. 7. Experiment results. Measured temporal waveforms and electrical spectrums of the generated 5 GHz triangular-shaped waveforms with tunable symmetrical coefficient.

ideal waveforms is 0.0457, which fits well with the theoretical RMSE value of 0.03103 as shown in Fig. 5, which demonstrates the proposed structure can generate a symmetrical triangular waveform with the tolerable error.

We then investigate the generation of triangular-shaped waveforms with tunable symmetrical coefficients based on the proposed scheme. In this case, we still fix the RF modulation index of 1.5, which corresponds to the power value of SG as 18.3 dBm. By adjusting the DC bias values, the waveforms with the symmetrical coefficients varying from 35% to 65% can be obtained, as shown in Fig. 7. When the DC bias is fixed as 3.56 V corresponding to $\theta = 0.646\pi$ rad, a measured triangular-shaped waveform with the symmetrical coefficient $\delta = 35\%$ can be obtained, as shown in Fig. 7(a) by the solid line. The ideal triangular waveform with the same symmetrical coefficient is also given in Fig. 7(a) by the dotted line. Fig. 7(b) gives the corresponding power values of first three harmonics, which are respectively -38.42 dBm, -50.28 dBm, and -58.66 dBm. Obviously, the obtained values agree well with the theoretical magnitude ratio of 1.2467: 0.2830: 0.0243, which is derived based on (8). We also calculate the RMSE of the measured waveform as 0.063, which is very close to the theoretical RMSE of 0.05736. Then we fix the DC bias as 3.35 V corresponding to $\theta = 0.609\pi$rad, both the measured and ideal waveforms with the symmetrical coefficient value of $\delta = 40\%$ are given in Fig. 7(c). Fig. 7(d) presents the captured power values of first three measured harmonics, which are respectively -37.65 dBm, -54.28 dBm and -58.24 dBm, which fit well with the theoretical magnitude ratio of 1.2614: 0.1949: -0.0866 obtained from (8). The RMSE of the measured waveform is also calculated as 0.0620, which fits with the theoretical value of 0.04959. Similarly, we further fix the DC biases as 3.12V, 2.43V, 2.15V and 1.95V respectively, the measured and ideal temporal waveforms with the symmetrical coefficient as $\delta = 45\%$, $\delta = 50\%$, $\delta = 55\%$, $\delta = 60\%$ and $\delta = 65\%$ are given in Fig. 7(e), (g), (i), (k) and (m). The corresponding spectra are shown in Fig. 7 (f), (h), (j), (o) and (n). The power values of the first-, second- and third-order harmonics can be measured as (-37.37 dBm, -60.51 dBm and -57.71 dBm),

(-37.25 dBm and -57.67 dBm), (-37.4 dBm, -59.72 dBm and -57.86 dBm), (-37.79 dBm, -53.38 dBm and -58.61 dBm), (-38.14 dBm, -50.42 dBm and -58.67 dBm) respectively, which fit well with the theoretical magnitude values. Meanwhile, according to (11), the RMSE of the measured waveforms can be calculated as 0.0663, 0.0457, 0.0699, 0.0638 and 0.0687 by comparing with the ideal waveforms, all of which validate the feasibility of the proposed approach.

IV. Conclusion

In this paper, a novel and simple approach for photonic generation of symmetry-tunable full-duty triangular-shaped waveform is proposed and experimentally demonstrated. A simple commercial single-drive Mach-Zehnder modulator (MZM) is adopted and driven by the RF input signal. By properly presetting the RF modulation index and simply adjusting the bias voltages of MZM, the full-duty triangular-shaped waveforms with any self-defined symmetrical coefficient from 34% to 66% can be obtained. A proof-of-concept experiment is carried out and the symmetry-tunable triangular waveforms with tolerable error ($\eta < 7\%$) at the repetition rate of 5 GHz are successfully generated.

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