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A novel approach to photonic generation of periodic triangular radio frequency waveforms

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A novel approach to photonic generation of triangular radio frequency waveforms with a tunable repetition rate is proposed and analyzed. In the proposed system, a continuous-wave light is modulated by a reference microwave signal through a polarization modulator, and then its output optical sidebands are manipulated by a microwave photonic filter with a negative tap. By properly adjusting the system parameters, full-duty-cycle triangular radio frequency waveforms can be generated after optical-to-electrical conversion, and its repetition rate (frequency) can be tuned in a wide range. A model describing the proposed system is derived, which is verified via computer simulations.

Keywords: microwave photonics, triangular waveform, polarization modulator (PolM), microwave photonic filter (MPF), radio frequency (RF) waveform generation.

1. Introduction

Photonic arbitrary waveform generation has attracted extensive attention over the past few years, and it is now widely regarded as one of the most important branches of the emerging discipline of microwave photonics [1]. Recently the generation of triangular radio frequency (RF) waveforms in the optical domain has become a topic of interest due to its various application fields such as testing, data display and all-optical signal processing and system [2, 3]. Photonic generation of triangular waveforms can overcome the frequency bottleneck of electronics methods and fully explore the advantages offered by modern optics such as small size, large tunability and immunity to electromagnetic interference. Up to now, many approaches have been proposed to generate triangular waveforms in the optical domain. By and large, the existing approaches can be classified into three categories: 1) time domain optical pulse shaping; 2) frequency domain optical pulse shaping followed by frequency-to-time mapping (FTTM); 3) Fourier synthesis.

In the first category, a typical scheme is to send short optical pulses through a length of nonlinear dispersive fiber [4]. By properly choosing the system parameters, such as pulse power, fiber dispersion and nonlinearity value, the input optical pulses can be shaped into triangular pulses. However this technique lacks flexibility because the desired dispersion and nonlinearity were difficult to manipulate for real application. Time domain pulse shaping has also been realized using a symmetrical shaper consisting of two conjugate dispersive elements and an electro-optic modulator [5]. However microwave sinc pulses were needed for the generation of triangular waveform, making the scheme costly and complicated to implement. Chirped fiber Bragg gratings (FBGs) were also used to shape optical pulses into triangular waveform [6], which again lacks flexibility due to the fixed response of FBGs. In the second category, a typical scheme is to transmit short optical pulses, generated by a mode locked laser (MLL), through an optical spectrum shaper to obtain an optical spectrum with a triangular shape. Then a piece of dispersive medium is used to perform the FTTM function that directly maps the envelope of the optical spectrum to triangular temporal waveforms [7]. However, the use of the MLL leads to higher system cost. Moreover the generated triangular waveforms usually have small duty cycle (<1). For many applications, triangular waveforms with full-duty-cycle are highly desired [2]. In the third category, optical frequency comb (OFC) signals are sent to a spatial light modulator (SLM) to perform line-by-line Fourier synthesis [8], where arbitrary waveforms, including triangular waveforms, can be generated. However the use of a SLM makes the system bulky and lossy, besides the need of OFC generator significantly increases the system cost and complexity.

External modulation of a continuous-wave (CW) light was demonstrated to be simple and cost-efficient substitutes to Fourier synthesize based triangular waveform generation [9–12]. In these schemes, input CW light is modulated by a reference microwave signal through a Mach–Zehnder modulator (MZM) with dual-drive [9] or dual-parallel configurations [10], then by properly setting the system parameters or using optical filtering [11, 12], the output optical sidebands from the modulator can be manipulated in the optical domain. As a result, the desired microwave harmonics corresponding to the Fourier components of triangular waveforms can be generated after optical-electrical conversion of the tailored optical signals by a photodiode (PD). However in [9], the formation of the generated triangular waveform was based on the dispersion of a fiber span, which is inconvenient to reconfigure for waveform frequency tuning. In [10], an extra 90° hybrid electrical coupler was required, which may subject to the electronic bottleneck problem. In [11] and [12], an optical interleaver or an optical bandpass filter was required to filter out unwanted optical sidebands, which may limit the frequency tuning range of the generated triangular waveform. Moreover the MZM used in the aforementioned schemes needs sophisticated bias control due to its bias drift problem, which may also increase the system's cost and complexity. In [13], a polarization modulator (PolM) was adopted instead of the MZM, but the bi-directional use of the PolM in a Sagnac loop structure is bulky and vulnerable to environment disturbance.

In this paper, a novel approach to photonic generating triangular RF waveforms is proposed. In the proposed system, input CW light is modulated by a PolM driven by a reference microwave signal, and the even-order optical sidebands are suppressed by a tunable microwave photonic filter (MPF) structure. By properly choosing system parameters, only odd-order harmonics are kept to obtain triangular RF waveforms after PD detection. And the repetition rate of the generated triangular waveforms can be tuned conveniently in a wide range. The proposed scheme is verified by theoretical analysis and the generation of full-duty-cycle triangular RF waveforms is demonstrated via computer simulations.

2. Principle and theoretical analysis

The schematic diagram of the proposed photonic triangular waveform generation system is shown in Fig. 1, which mainly consists of a laser diode (LD), a PolM, a PD, a tunable optical delay line (ODL), two polarization controllers (PCs), and a pair of polarization beam splitter/combiner (PBS/PBC). In the system, the PolM in conjunction with the PBS can operate as an equivalent intensity modulator (IM) [13], therefore multiple optical sidebands can be generated at the output of the PBS. Furthermore, the following PBS/PBC pair with the ODL can function as a tunable two-tap MPF with a negative tap [14], which, through appropriate configuration, can eliminate the unwanted even-order optical sidebands outputting from the equivalent IM (as indicated in the insert of Fig. 1).

The light carrier from the LD is sent to the PolM which is driven by a sinusoidal reference microwave (RM) signal. The PolM is a special phase modulator that can support both TE (transverse electronic) and TM (transverse magnetic) modes with, however, opposite phase modulation indices. When the linearly polarized incident light is oriented with an angle of 45° to one principal axis of the PolM (by adjusting PC1),

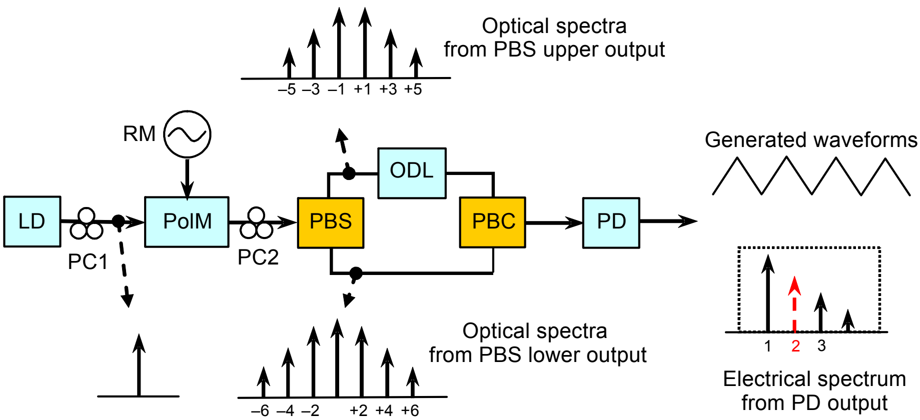

Fig. 1. Schematic diagram of the proposed triangular waveform generation system. LD – laser diode, PolM – polarization modulator, PBS – polarization beam splitter, PBC – polarization beam combiner, PC – polarization controller, ODL – tunable optical delay line, PD – photodetector.

complementary phase modulated optical signals are generated along its two principal axes. The normalized optical fields at the output of the PolM can be expressed as [15]:

$$\begin{bmatrix} E_x(t) \\ E_y(t) \end{bmatrix} \propto \exp(j\omega_c t) \begin{bmatrix} \exp\left(j\beta \dfrac{\Phi(t)}{2}\right) \\ \exp\left(-j\beta \dfrac{\Phi(t)}{2}\right) \end{bmatrix} \tag{1}$$

where ω_c is the angular frequency of the light carrier, $\Phi(t)$ is the normalized reference microwave signal which can be expressed as $\Phi(t) = \sin(\omega_m t)$, with ω_m being its angular frequency. Parameter β is the modulation index which can be expressed as $\beta = \pi V_m / V_\pi$, with V_m and V_π being the amplitude of the RM signal and the half-wave voltage of the PolM, respectively. The optical signals are then sent to the PBS through PC2, which is used to align the principal axes of the PolM to have an angle of 45° to those of the PBS. Then the two outputs from the PBS are combined by a PBC, with one output delayed by the ODL. Therefore the optical fields from the PBC along the two principal axes can be written as

$$\begin{bmatrix} E'_x(t) \\ E'_y(t) \end{bmatrix} \propto \begin{bmatrix} E_y(t) + E_x(t) \\ E_y(t-\tau) - E_x(t-\tau) \end{bmatrix} =$$

$$= \exp(j\omega_c t) \begin{bmatrix} \exp\left(j\beta \dfrac{\Phi(t)}{2}\right) + \exp\left(-j\beta \dfrac{\Phi(t)}{2}\right) \\ -\exp(j\omega_c \tau)\left[\exp\left(j\beta \dfrac{\Phi(t-\tau)}{2}\right) - \exp\left(-j\beta \dfrac{\Phi(t-\tau)}{2}\right)\right] \end{bmatrix} \tag{2}$$

where τ is the time delay induced by the ODL. Then after optical-electrical conversion by the PD, the output RF signal can be written as:

$$I(t) \propto \left|E'_x(t)\right|^2 + \left|E'_y(t)\right|^2 \propto 2 + \cos[\beta\,\Phi(t)] - \cos[\beta\,\Phi(t-\tau)] \tag{3}$$

Considering the expression of the reference microwave signal, Eq. (3) can be rewritten as

$$I(t) \propto A_0 + 2\left\{ \sum_{n=1}^{\infty} J_{2n}(\beta)\cos(2n\omega_m t) - \sum_{n=1}^{\infty} J_{2n}(\beta)\cos[2n\omega_m(t-\tau)] \right\} \approx$$

$$\approx A_0 + 2J_2(\beta)[\cos(2\omega_m t) - \cos(2\omega_m t - 2\omega_m \tau)] +$$

$$+ 2J_4(\beta)[\cos(4\omega_m t) - \cos(4\omega_m t - 4\omega_m \tau)] +$$

$$+ 2J_6(\beta)[\cos(6\omega_m t) - \cos(6\omega_m t - 6\omega_m \tau)] + \ldots \tag{4}$$

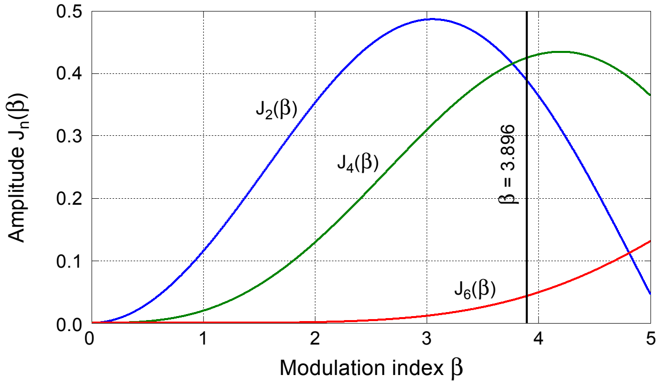

Fig. 2. The relationship between $J_n(\beta)$ and β.

where A_0 stands for a DC component, which can be eliminated by a DC block when necessary, and $J_n(\beta)$ is the Bessel function of the first kind of order n. It is known that the Fourier series expansion of a triangular waveform can be expressed as

$$T(t) \propto \mathrm{DC} + \sum_{m\,=\,1,\,3,\,5}^{\infty} \frac{1}{m^2} \cos(m\Omega t) \approx \mathrm{DC} + \cos(\Omega t) + \frac{1}{9}\cos(3\Omega t) + \ldots \tag{5}$$

where Ω is its repetition rate (frequency). It can be seen that high-order harmonics with a fast roll-off factor have little impact on the waveform, so triangular waveform can be approximately represented with its first two harmonics, where only an average error of 1.1% will be induced [16]. Comparing Eq. (4) with Eq. (5), it can be inferred that triangular waveform can be obtained when the following two conditions are met in Eq. (4), namely: $2\omega_m \tau = \pi$ and $J_6(\beta)/J_2(\beta) = 1/9$. The first condition can be realized by tuning the ODL, making $\tau = \pi/2\omega_m$. The relationship of $J_n(\beta)$ *versus* β is computed and visualized using MATLAB software, as shown in Fig. 2. As can be seen, the second condition can be met when $\beta = 3.896$. Since $\beta = \pi V_m/V_\pi$, this condition can be realized by properly tuning V_m.

3. Simulation results and discussions

To further investigate the proposed triangular waveform generation system, a simulation model is setup (using a commercial software package *VPItransmission Maker*), as shown in Fig. 3. The simulation model is based on the schematic diagram in Fig. 1, where CW light wave from the LD has a wavelength of 1550 nm, and a linewidth of 1 MHz. The input reference microwave (RM) signal is a tunable sinusoidal wave. By properly adjusting the amplitude of the RM signals as well as the ODL, triangular waveforms with tunable repetition rate can be generated.

Firstly, the frequency of the RM signal is set as $f_m = 5$ GHz. According to the theoretical analyses in the previous section, ODL should be tuned so that the time delay

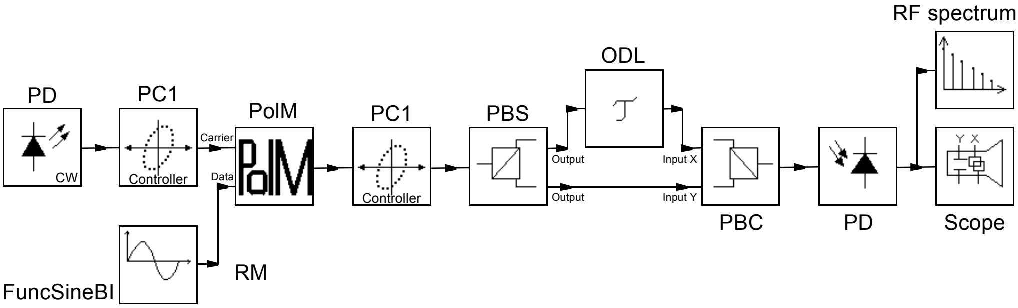

Fig. 3. The simulation model.

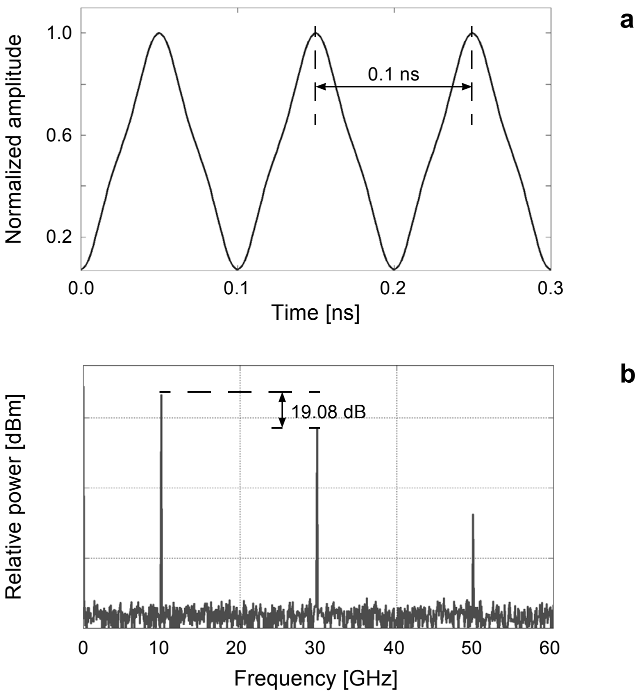

Fig. 4. The generated triangular waveform (**a**) and its spectrum (at the repetition rate of 10 GHz) (**b**).

is set as $\tau = 50$ ps. Figures 4**a** and 4**b** show the generated triangular waveform and its spectrum, respectively.

As seen from Fig. 4**a**, a full-duty-cycle triangular waveform is generated, which has a repetition period of 0.1 ns, indicating the repetition frequency is 10 GHz. This consists with the theoretical analysis. As seen from Fig. 4**b**, the spectrum of the generated triangular waveform is composed of DC, 10 GHz, 30 GHz and 50 GHz harmonic components, where the power of the 30 GHz component is 19.08 dB lower than that of the 10 GHz component, indicating the amplitude of its third-order harmonic is 1/9

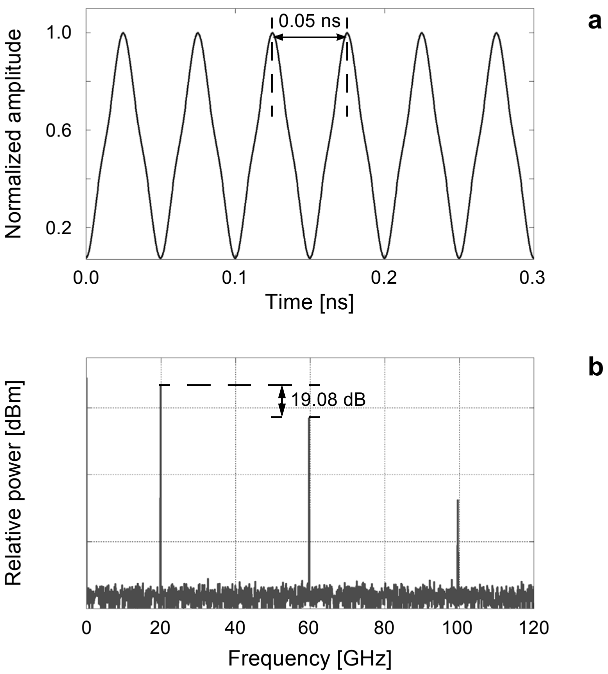

Fig. 5. The generated triangular waveform (**a**) and its spectrum (at the repetition rate of 20 GHz) (**b**).

of that of its first-order harmonic. The fifth-order harmonic at 50 GHz is 68 dB lower than the first-order harmonic in power, thus has little impact on the generated triangular waveform.

Secondly, the tunability of the proposed triangular waveform generation system is also verified. In this case, the frequency of the RM signal is tuned to be $f_m = 10$ GHz, and the time delay of ODL is adjusted as $\tau = 25$ ps, while other system parameters are unchanged. According to our theoretical analyses, the repetition frequency of the generated triangular waveform will be changed to 20 GHz. Figures 5**a** and 5**b** show the generated triangular waveform and its spectrum, respectively.

As seen from Fig. 5**a**, the repetition period of the generated triangular waveform is 0.05 ns. Therefore its repetition frequency is 20 GHz, which confirms our theoretical prediction. As can be seen from Fig. 5**b**, the spectrum of the generated triangular waveform has three harmonics at 20, 60, and 100 GHz, respectively. Again, the power of its third-order harmonic at 60 GHz is 19.08 dB lower than that of its first-order harmonic at 20 GHz, which indicates the amplitude of its third-order harmonic is 1/9 of that of its first-order harmonic. The fifth-order harmonic can be neglected since its amplitude is 70 dB lower than that of the first-order harmonic.

In the proposed system, the PCs need to be controlled so that the modulated light signals from the PolM can be launched into the PBS with a 45° polarization angle to its principal axes to perform intensity modulation. In real-life application, however, this polarization angle may drift away from 45° due to environment disturbance. Generally, the included angle between the principal axes of the PolM and the PBS can be assumed as α ($0° < \alpha < 90°$). Then the Eq. (2) in our theoretical analysis section is necessary to be amended to include this factor as follows:

$$\begin{bmatrix} E'_x(t) \\ E'_y(t) \end{bmatrix} \propto \begin{bmatrix} \cos(\alpha)E_y(t) + \sin(\alpha)E_x(t) \\ \cos(\alpha)E_y(t-\tau) - \sin(\alpha)E_x(t-\tau) \end{bmatrix} =$$

$$= e^{j\omega_c t} \begin{bmatrix} \cos(\alpha)e^{-j\beta\Phi(t)/2} + \sin(\alpha)e^{j\beta\Phi(t)/2} \\ -e^{j\omega_c\tau}\left[\sin(\alpha)e^{j\beta\Phi(t-\tau)/2} - \cos(\alpha)e^{-j\beta\Phi(t-\tau)/2}\right] \end{bmatrix} =$$

$$= e^{j\omega_c t} \begin{bmatrix} [\sin(\alpha) - \cos(\alpha)]e^{j\beta\Phi(t)/2} + 2\cos(\alpha)\cos\left(\beta\dfrac{\Phi(t)}{2}\right) \\ -e^{j\omega_c\tau}\left[[\sin(\alpha) - \cos(\alpha)]e^{j\beta\Phi(t-\tau)/2} + 2j\cos(\alpha)\sin\left(\beta\dfrac{\Phi(t-\tau)}{2}\right)\right] \end{bmatrix} \tag{6}$$

As can be seen from Eq. (6), if α drifts away from 45°, the PolM actually performs amplitude modulation and phase modulation simultaneously. Since PD only detects the amplitude of the signal, the phase modulation component will be eliminated after PD detection, then Eq. (3) in our theoretical analysis section needs to be rewritten as

$$I(t) \propto A(\alpha) + \sin(2\alpha)[\cos(\beta\Phi(t)) - \cos(\beta\Phi(t-\tau))] \tag{7}$$

where $A(\alpha)$ is a DC component related to α, which can be eliminated by a DC blocker. Then the expression of the RM signal is considered, and the succeeding mathematics derivation is similar to that used for Eq. (4). Similarly, if the two conditions described in the theoretical analysis are met by adjusting τ and V_m, triangular waveforms can be generated. The difference is that, as can be inferred from Eq. (7), the change of α will have impacts on the amplitudes of the generated triangular waveform. In extreme cases, when α approaches 0° or 90°, triangular waveforms will never be generated because PolM only perform phase modulation under these conditions. But as long as α varies within the neighborhood of 45°, the system output can retain triangular waveforms.

A simulation is implemented to verify the theoretical analysis. In this simulation scenario, the system parameters are set as f_m = 5 GHz, τ = 50 ps. And the polarization angle α is varied to be 45°, 50° and 60°, respectively. For ease of comparison, the generated triangular waveforms in each case are superimposed and shown in Fig. 6. (The amplitudes of the generated waveforms are normalized to their common maximum value, with their DC components eliminated using a DC blocker.)

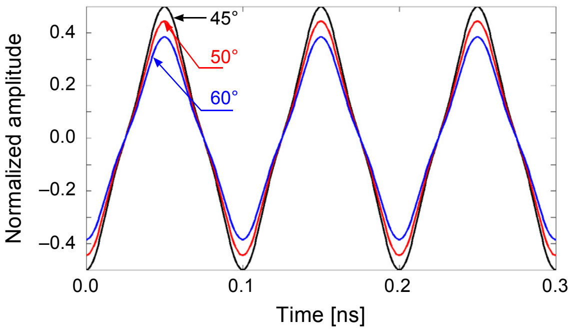

Fig. 6. The generated triangular waveforms with different polarization angles α.

As can be seen, when α is increased from 45° to 50° and 60°, the amplitudes of the generated triangular waveforms are slightly decreased, which can be confirmed by Eq. (7). Similarly, if α is decreased from 45°, the amplitude of the generated triangular waveforms will also decrease. Therefore, the system polarization drift can have some impacts on the amplitude and the DC component of the generated triangular signals. On the other hand, it can be seen that when α is increased to 50° and 60° (or decreased to 40° and 30°) from its desired value 45°, the amplitudes of the generated triangular waveforms will drop 11% and 23%, respectively, from its maximum value when α is 45°. Since the signal amplitude decrease can be compensated by optical or electrical amplification, the system output can retain triangular waveform when the variation of α is within the range of 15° from 45°. Therefore, it can be concluded that a small amount of polarization mismatch or drifts can be tolerable in our system.

In the proposed system, the frequency tuning range of the generated triangular waveform is mainly limited by the bandwidth of PolM and PD. Since 40 GHz PolM and 100 GHz PD are commercially available, the tuning range can reach to tens of GHz. Besides, since no optical bandpass filters and fiber dispersion are needed in the waveform generation process, the repetition rate of the generated triangular RF waveform can be continuously and conveniently tuned in a wide range. On the other hand, the frequency tuning step size is mainly decided by the tuning step of the ODL. Since ODL with a tuning step size less than 1 ps is commercially available, fine and accurate frequency tuning of the generated triangular waveform is also feasible.

Besides, in our theoretical analysis and simulations the half-wave voltage V_π of PolM is taken as a constant. However, the V_π of a real-life PolM can be slightly higher when the frequency of its driving RF signals is increased. The change of V_π can affect the value of modulation index β, which in turn will affect the generation of triangular waveforms. In order to compensate this change, the amplitude of its driving signal V_m should be adjusted accordingly to keep the value of modulation index β as required for the generation of triangular waveforms. An experimental study will be necessary to further investigate the proposed system, which will be our future work when required lab facilities are available.

4. Conclusion

A novel approach to photonic generation of full-duty-cycle RF triangular waveform with a tunable repetition rate is proposed and verified by theoretical analysis and computer simulations. The proposed scheme is based on optical subcarrier modulation using polarization modulation followed by optical sidebands manipulating by a two tap microwave photonic filter (MPF) structure with one negative tap, by which the Fourier components of a triangular waveform are generated. The proposed scheme is simple, and the repetition rate of the generated triangular waveform can be finely turned in a wide frequency range. Moreover, since the PolM and ODL used in the proposed system can be integrated, a stable and compact triangular waveform generator can be realized based on the proposed approach.

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