

# Review on photonic method for generating optical triangular pulses

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**Abstract** In this paper, several photonic generating methods for optical triangular pulses were reviewed. Four frontier research methods for generating optical triangular pulses were introduced, these four methods are respectively based on the frequency-to-time conversion, using normally dispersive fiber, by single-stage dual-drive Mach-Zehnder modulator (MZM), and using dual-parallel MZM. These four methods can be classified into two categories in terms of the optical source employed, such as mode-lock laser (MLL) and continuous-wave (CW) respectively. Compared with the methods based on MLL, those based on CW have many advantages, such as simpler structure, lower price, higher stability, more flexible and wider tunability. Besides, the method using single-stage drive MZM can generate versatile waveform optical pulses, which has better performance than the first two methods in tunable capability of both repetition rate and center wavelength. With the same driving signal applied, the optical source using the dual-parallel MZM can generate signal with higher frequency than that of using the single-stage MZM.

**Keywords** triangular pulses, Mach-Zehnder modulator (MZM), mode-lock laser (MLL), continuous-wave (CW)

## 1 Introduction

The growing demand of higher signal transmitting and processing frequency is a current challenge for pure electronic systems. Compared with their electrical counterparts, all-optical approaches offer many prominent advantages, such as high bandwidth, good reconfigurability and immunity to electromagnetic interference and so on [1]. As we all know, controlling the shape of optical pulses has

become increasingly important for many scientific applications, such as high speed optical communication system, quantum optics, and nonlinear optics. The possibility of changing the pulse waveform from the well-known shapes to more exotic triangular pulses could be of use for various applications in optical signal processing and manipulation. In all-optical fields, the generation of ultra-short pulses using photonic methods is a subject of constant active research. Triangular-shaped pulse is characterized with simple intensity profile and linear slope in waveform. Similar to a square waveform, it only consists of odd harmonics in spectrum. But its higher harmonics roll off much faster than square wave do. Therefore, it has been thought to have ideal waveform profile in signal processing, testing, and display both in electrical [2,3] and optical domain [4]. Currently, there are many common and relatively mature photonic technologies to generate optical triangular pulses, and we can group them into two categories according to the source type employed.

Currently, to generate optical triangular pulses, there are mainly two types of light sources, mode-lock laser (MLL), and continuous-wave (CW) source. MLL with compact structure, excellent performance, and stable mode-locked state, is becoming a promising work-horse in ultrafast laser research area. Thus, in the generation of the triangular pulses, MLL has been widely used, such as in the frequency-to-time mapping and all-optical shaping technologies. In addition to the MLL, CW is also widely employed because of its simplicity, low price, high stability, flexibility, wide tunability and so on. CW source often works together with Mach-Zehnder modulator (MZM), showing good performance.

## 2 Photonic methods for generating triangular pulses

MLL and CW source are two common sources used in

triangular pulses generating. Based on the used light source, we can divide the photonic methods into two categories.

## 2.1 Photonic methods for generating triangular pulses by using MLL

By using the MLL, frequency-to-time mapping (FTTM) and all-optical pulses shaping technologies can be implemented.

### 2.1.1 Photonic methods for generating triangular pulses based on FTTM [5]

An efficient photonic solution to generate electrical pulses has been proposed and demonstrated by using the approach based on the combination of the optical-spectrum-shaping method and the FTTM technique [5–8].

The FTTM technique is a conversion method, which can be used to directly map the envelope of the optical spectrum to the temporal waveform. Compared with the schemes based on a real-time Fourier transformer, it is more suitable for microwave signal generation because of its insensitivity to the optical phase [9–12]. At present, there are mainly two kinds of optical spectral shapers, the spatial light modulator (SLM) and the fiber-optic spectral filter. In the scheme proposed in Ref. [5], a fiber-optic based approach to generate periodic triangular-shaped pulses with frequency-to-time conversion was reported. The main idea of this approach is that the modulated pulse sequence from a broadband source is spectrally shaped by an optical spectrum shaper composed of two cascaded filter modules. In the experimental setting, a piece of dispersive fiber (or other dispersive media) and a photo-detector (PD) perform a FTTM function to generate

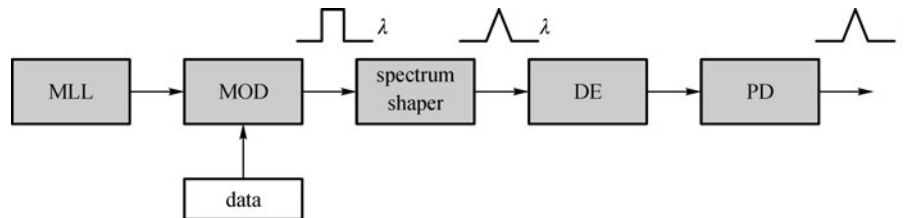
temporal triangular-shaped pulses.

The process of generating triangular-shaped pulse is shown in Fig. 1. The optical pulses generated by a MLL are sent to a modulator to adjust the pulse repetition rate. Then, an optical triangular spectrum is obtained by spectrally filtering the broadband ultra-short pulse sequence using a spectrum shaper based on polarization interference. Thanks to a FTTM module, which is composed of a dispersive fiber (or other dispersive medium) and a PD, the generated temporal pulses exhibit the same shape as the optical spectrum [10]. The width of the achieved triangular-shaped pulse can be set by tuning the fiber length in the FTTM module, because the system dispersion is the only factor that determines FTTM performance [13]. It should be noted that the tunable range of the pulse width is limited by the equation  $2\pi\beta_2z \gg |\Delta t_0^2|$ , where  $\beta_2$  is the constant of group velocity dispersion,  $\Delta t$  is the time width of the input pulse, and  $z$  is the fiber length. The triangular-shaped optical spectral shaping is a critical step of the pulse generation based on frequency-to-time conversion. Figure 2 shows the configuration of the spectrum shaper proposed in this scheme. Two cascaded sinusoidal filter modules and a bandwidth-tunable optical filter constitute the shaper. Each sinusoidal filter module is composed of two polarization controllers (PCs), a piece of polarization maintaining fiber (PMF), and a polarizer.

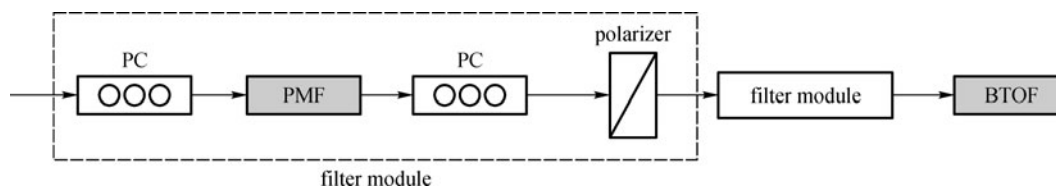
The frequency characteristic of the filter module can be described by the following equation:

$$f(\omega) = A_1[1 + a_1\cos(\omega T_1)], \quad (1)$$

where  $A_1$  denotes the fiber transmittance and  $T_1$  is the differential group delay (DGD) of the PMF. In addition,  $a_1$  is the extinction coefficient ranging from 0 to 1, which is determined by the status of the two PCs. Note that the second fiber module has the same configuration with the



**Fig. 1** Flow chart of triangular-shaped pulse generation (MLL, mode-locked laser; MOD, modulator; DE, dispersive element; PD, photo-detector)



**Fig. 2** Schematic diagram of spectrum shaper (PC, polarization controller; PMF, polarization maintaining fiber; BTOF, band-width-tunable optical filter)

first one, so the filter function of the spectrum shaper can be described as

$$\begin{aligned} f(\omega) &= A[1 + a_1 \cos(\omega T_1)][1 + a_2 \cos(\omega T_2)] \\ &= A\{1 + a_1 \cos(\omega T_1) + a_2 \cos(\omega T_2) \\ &\quad + \frac{a_1 a_2}{2} [\cos(\omega T_1 + \omega T_2) + \cos(\omega T_1 - \omega T_2)]\}. \end{aligned} \quad (2)$$

In this method, the second piece of PMF has three times the length of the first one, that is, we can make  $T_2 = 3T_1$ . And  $a_2$  is set to be one-ninth of  $a_1$ . When  $a_1$  and  $a_2$  are confined to be a small value in the range from 0 to 1, the fourth term is negligible. Based on this special value choice of the parameter, we can write Eq. (2) approximately by

$$f(\omega) = Aa_1 \left[ \frac{1}{a_1} + \cos(\omega T_1) + \frac{1}{9} \cos(3\omega T_1) \right]. \quad (3)$$

It is easy to find that the response function of the proposed spectrum shaper is similar to the expansion equation of a periodic triangular waveform as

$$\begin{aligned} f(t) &= B_1 + B_2 \left[ \cos(\omega t) + \frac{1}{9} \cos(3\omega t) + \frac{1}{25} \cos(5\omega t) + \dots \right]. \end{aligned} \quad (4)$$

Considering that  $B_1$  and  $B_2$  are the amplitude constants and the high-order harmonic components having ignorable effects in the synthesis function, that is, Eq. (4) is consistent with Eq. (3), we may think the cascade of two sinusoidal filter modules can achieve a triangular response function. Subsequently, use a bandwidth-tunable optical filter (BTOF) to filter out an individual triangular spectrum.

In this scheme, the repetition rate and the pulse width of the generated signals can be tuned by adjusting the modulation rate and the dispersion value respectively.

### 2.1.2 Photonic methods for generating triangular pulses by using all-optical pulses shaping technology [14]

The principle is to generate Gaussian-shaped pulses from

the MLL by passing through a length of spectrum-shaped material, which could be a highly nonlinear optical fiber links [14,15] or other optical units with nonlinear characteristic [5].

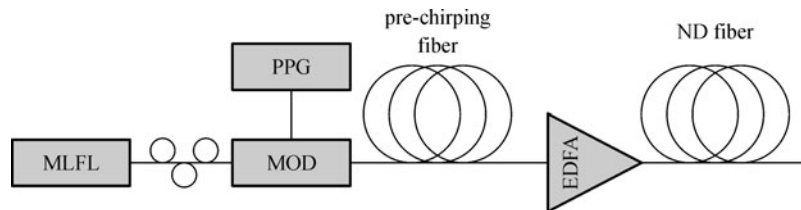
Boscolo et al. have presented an approach for passive nonlinear pulse shaping in the time domain, which relies on a combination of pulse pre-chirping and nonlinear propagation in a section of normally dispersive (ND) fiber [15]. And this passive pulse shaping scheme is based on Kerr nonlinearity and group-velocity dispersion (GVD) in a ND fiber. In addition, with the use of a pre-chirping device and an optical amplifier, the pulse shape and power can be adjusted at the fiber input to realize various reshaping process.

In particular, triangular-shaped pulses can only be generated with the premise of sufficiently high energies and a positive initial chirp parameter (using the definition for the phase profile). For example, a Gaussian-shaped pulse has been applied as the pulse input to the ND fiber [16]. Note that for a different choice of the initial pulse shape, pulse reshaping processes similar to those illustrated in Ref. [14] are expected to occur upon propagation in a ND fiber, whereas the relevant parameter regions would be different [16].

Experimental set-up for triangular-shaped pulses generation is shown in Fig. 3.

In Fig. 3, transform-limited pulses at certain frequency generated from a mode-locked fiber laser (MLFL) operating at certain wavelength, with a repetition rate of relative higher frequency (such as 10 GHz) are modulated down to a repetition rate of relative lower frequency (such as 1.25 GHz) using a lithium niobate Mach-Zehnder modulator (MOD). This ensures that sufficient pulse energy could be achieved at the relatively low saturated output power of the erbium-doped fiber amplifier (EDFA).

The pulse's pre-chirping value can be controlled by making the pulse propagate through different lengths of standard single-mode fiber (SMF), the SMF used in Ref. [14] had a positive dispersion coefficient  $D = -2\pi c\beta_2/\lambda^2 = 16.3 \text{ ps} \cdot \text{nm}^{-1} \cdot \text{km}^{-1}$  at  $\lambda = 1550.0 \text{ nm}$  and it imposed a positive chirp parameter  $C'$  on the pulse. The EDFA was applied to amplify the pre-chirped pulses to different power levels, and then the pulses propagated through a ND fiber to realize the pulse reshaping. It could be found from the final generated pulses that the chirp is highly linear



**Fig. 3** Experimental set-up for triangular-shaped pulses generation (MLFL, mode-locked fiber laser; PPG, pulse pattern generator; MOD, modulator; EDFA, erbium-doped fiber amplifier; ND fiber, normally dispersive fiber)

across the entire pulse duration. This is an additional attractive feature of the triangular pulses generation for all-optical signal processing applications. The passive nonlinear pulse shaping method described here thus offers an attractive and simple way of generating triangular pulses.

As for the other two methods for generating triangular pulses, there were also several other schemes reported. In 2001, the researchers in the University of Southampton first proposed a method using a super-structured fiber Bragg grating (SSFBG) to generate the triangular-shaped pulses [17]. In 2007, Park et al. also presented that triangular optical pulses can be obtained based on temporal coherence synthesization using a multi-arm interferometer [18].

As we know, the technologies all adopted the active or passive MLL based on semiconductor or fiber-optic technologies to generate pulse trains. In these technologies, the laser cavity should be strictly designed and stabilized to generate stable pulse trains, which reduces flexibility in the operation. Especially, its repetition rate of the generated pulses is almost fixed, which determines scarce tunability which it can provide. Also, the common and highly nonlinear properties involved in the process of generating pulses restrict its operating conditions, leading to limited output optical power and uncontrollable chirp characteristics [19].

## 2.2 Photonic methods of generating triangular pulses by using CW source

Owing to the good stability and the high coherence of the pulse comb generated from the electro-optic (EO) modulator [19], a pulse source consisting of a CW laser diode (LD) and an external modulator is a promising alternative on generating pulses, which can exhibit excellent stability and low timing jitter. Its repetition rate can be easily controlled by the synthesizer acting as a modulator driver. Moreover, its configuration is compact, straightforward, and reliable [20]. In addition, compared with the MLL, which is very complex and expensive, CW

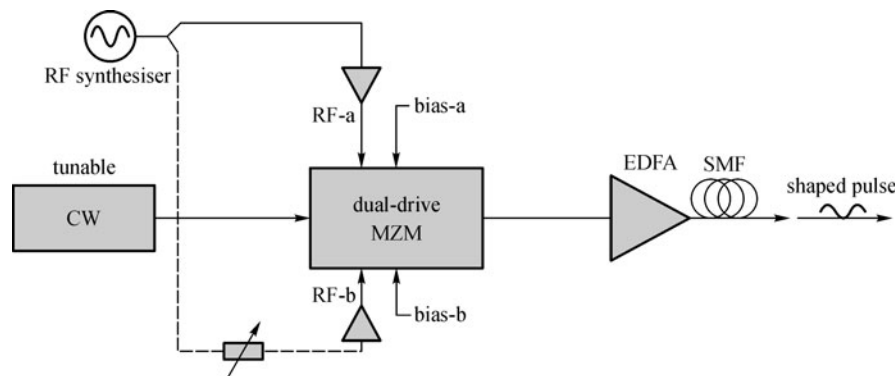
source is low-priced and simple. Currently, the price of commercial levels of CW source is only about thousands of dollars, so it is widely used in various fields of optical fiber communication.

To our knowledge, many studies on the generation of the optical frequency comb have been carried out, which can be used for ultra-short pulse generation. In previous reports, it has been proposed that two modulators (an optical phase modulator and a MZM) can be cascaded in tandem to obtain a flat spectral envelope [20]. In addition, the pulse trains with sync<sup>2</sup>-or Gaussian-like temporal waveform with 2.4 ps pulse at a repetition of 10 GHz was generated by using a single-stage MZM, and an optical thin-film filter for spectra shaping [19]. Recently, there are some papers reported that programmable optical processor has been used to manipulate the amplitude and phase of the generated frequency comb lines [21]. The research results of the frequency comb also contribute to the emergency of a new regime for optical arbitrary waveform [22,23] including triangular-shaped pulses generation.

### 2.2.1 Scheme based on the single-stage dual-drive MZM

Recently, a good proposal using the single-stage dual-drive MZM to generate and manipulate the optical comb has been put forward in Ref. [24], it is a versatile waveform generating set-up based on the principle of electro-optic (EO) modulator. The schematic diagram is shown in Fig. 4.

In Fig. 4, the system is composed of two main sections: comb generation and waveform formation. In the comb generation part, a CW light is generated from a laser diode and then directed into the dual-drive LiNbO<sub>3</sub> MZM. The 10 GHz radio frequency (RF) sinusoidal signal is generated from an RF synthesizer, then divided into half (RF-a and RF-b) with a hybrid coupler, and amplified by a microwave amplifier to drive the dual-drive MZM. The relative amplitudes ( $A_1$  and  $A_2$ ) and phase difference of the two RF signals can be adjusted by the RF attenuator and the tunable delay line. Undergoing the process of EO modulation, an optical frequency comb with multiple



**Fig. 4** Experimental set-up using single-stage dual-drive MZM for waveform generation (RF, radio frequency; CW, continuous-wave; MZM, Mach-Zehnder modulator; EDFA, erbium-doped fiber amplifier; SMF, single-mode fiber)

sidebands on both sides of the fundamental component is generated. The electric field of the output signal from the MZM is given by [19]

$$E_{\text{out}} = \frac{1}{2} E_{\text{in}} \sum_{k=-\infty}^{\infty} [J_k(A_1) e^{j(k\omega t + \theta_1)} + J_k(A_2) e^{j(k\omega t + \theta_2)}], \quad (5)$$

where  $J_k$  is the  $k$ -th order Bessel function and  $\theta_{1,2}$  are the DC biases for each arm. In the waveform formation section, in order to compensate for the frequency chirp induced by the EO modulation, the generated comb signal is converted to the pulse-shaped signal, including symmetric triangular, saw tooth, flat-top, sinusoidal, and doublet shaped pulses. According to Ref. [25], this scheme has relatively wide tunable-repetition. Considering signals are all at the repetition rate of 10 GHz, that is, the generated pulses have the same repetition rate with the RF driving signal, we can change the repetition rate of the generated signals if we use the RF signal at different repetition rates. In addition, it should be noted that since the frequency comb generation is independent of the wavelength of the input CW light, therefore, by adjusting the centre wavelength of the CW laser source, the scheme proposed in Ref. [24] has the potential to generate waveforms at different centre wavelengths.

The tunable capability of both repetition rate and centre wavelength makes this scheme particularly attractive as a waveform generation source for photonic network.

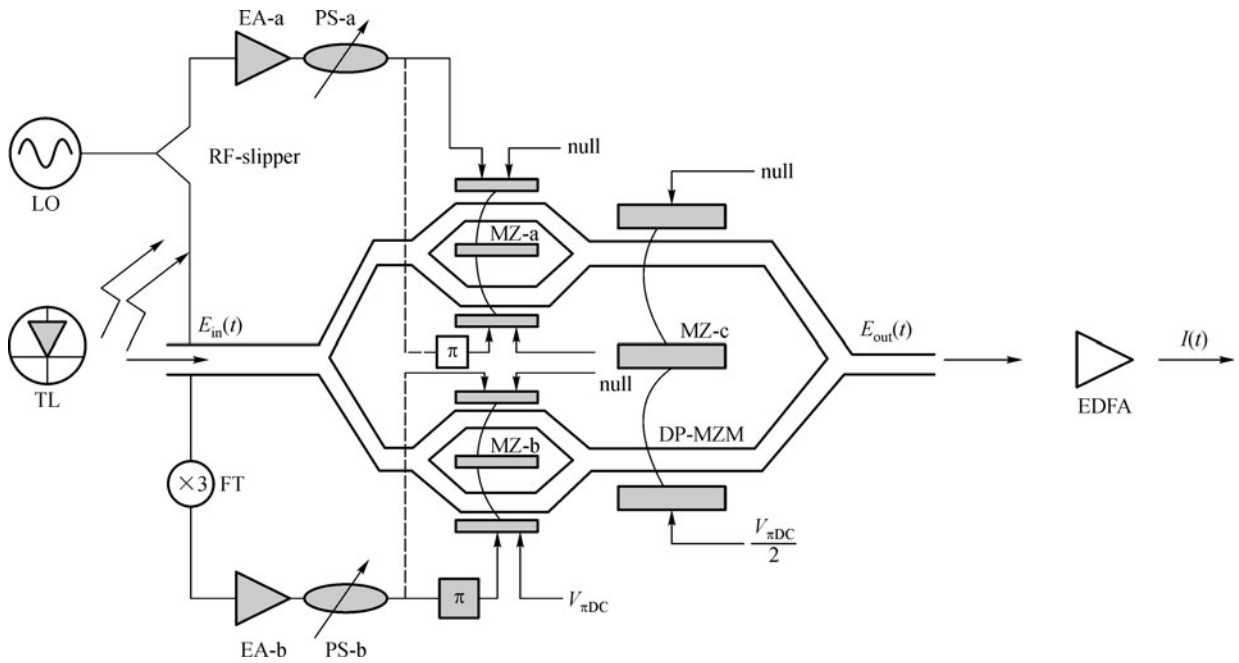
## 2.2.2 Photonic generation of triangular waveform signals by using a dual-parallel MZM [26]

In Ref. [26], Li et al. has proposed a method of generating the triangular waveform signals based on a dual-parallel MZM (DP-MZM). The main thought of this method is described as follows: firstly, the bias between MZ-a and MZ-b is made at the minimum transmission point; secondly, a sinusoid local oscillator (LO) is employed as the driving oscillator, the width of the pulses can be tuned by changing the LO frequency.

The schematic setup is shown in Fig. 5. A tunable laser (TL) serves as the optical source. Light wave signals are coupled into a DP-MZM for modulation. Driving signals of MZ-a and MZ-b are generated from the same LO. The difference is that a frequency tripler (FT) is used in the lower path, resulting in a frequency multiple (3 time) of the driving signals. Then two electrical amplifiers (EA-a and EA-b) and two phase-shifters (PS-a and PS-b) are used to set amplitude and initial phase of driving signals. Because of x-cut design, MZ-a and MZ-b are configured for push-pull operation and all three sub-MZMs have independent DC bias.

The output optical field of the DP-MZM is

$$E_{\text{out}} = \frac{E_{\text{in}}(t)}{\sqrt{t_{\text{ff}}}} \{ \gamma_1^2 \exp[jm_1 \sin(\omega t + \theta(t))] + \gamma_1 \gamma_2 \exp[-jm_1 \sin(\omega t + \theta(t)) + j\phi_1] + \gamma_1 \gamma_2 \exp[jm_2 \sin(3\omega t + 3\theta(t)) + j\phi_3] \}$$



**Fig. 5** Schematic set-up using a dual-parallel MZM for the triangular-shaped pulses (TL, tunable laser; LO, local oscillator; FT, frequency tripler; EA, electrical amplifier; PS, phase-shift; DP-MZM, dual-parallel Mach-Zehnder modulator; EDFA, erbium-doped fiber amplifier)

$$+\gamma_2^2 \exp[-jm_2 \sin(3\omega t + 3\theta(t)) + j\varphi_2 + j\varphi_3] \}. \tag{6}$$

After amplification of an EDFA, the intensity  $I(t)$  can be expressed as

$$\begin{aligned} I(t) = & \frac{GE_0^2(\gamma_1^4 + 2\gamma_1^2\gamma_2^2 + \gamma_2^4)}{2t_{ff}} \\ & + \frac{GE_0^2}{t_{ff}} \{ \gamma_1^3\gamma_2 \cos[2m_1 \sin(\omega t + \theta(t)) - \varphi_1] \\ & + \gamma_1\gamma_2^3 \cos[2m_2 \sin(3\omega t + 3\theta(t)) - \varphi_2] \} \\ & + \frac{GE_0^2}{t_{ff}} \{ \gamma_1^3\gamma_2 \cos[m_1 \sin(\omega t + \theta(t)) \\ & - m_2 \sin(3\omega t + 3\theta(t)) - \varphi_3 \\ & + \gamma_1\gamma_2^3 \cos[m_1 \sin(\omega t + \theta(t)) \\ & - m_2 \sin(3\omega t + 3\theta(t)) - \varphi_1 + \varphi_2 + \varphi_3] \\ & + \gamma_1^2\gamma_2^2 \cos[m_1 \sin(\omega t + \theta(t)) \\ & + m_2 \sin(3\omega t + 3\theta(t)) - \varphi_1 + \varphi_3] \\ & + \gamma_1^2\gamma_2^2 \cos[m_1 \sin(\omega t + \theta(t)) \\ & + m_2 \sin(3\omega t + 3\theta(t)) - \varphi_2 - \varphi_3] \}. \tag{7} \end{aligned}$$

To investigate the principle, the extinction ratio is assumed to be infinite firstly and the bias is set according to Fig. 5, which make  $\gamma_1 = \gamma_2$ , then  $I(t)$  can be rewritten as

$$\begin{aligned} I(t) = & \frac{GE_0^2}{8t_{ff}} - \frac{GE_0^2}{16t_{ff}} \{ \cos[2m_1 \sin(\omega t + \theta(t))] \\ & + \cos[2m_2 \sin(3\omega t + 3\theta(t))] \}. \tag{8} \end{aligned}$$

Then expand Eq. (8) with the Bessel function, consider only frequency components up to second-harmonic, and adjust the modulation index to meet the following relationship

$$J_2(2m_1) = 9J_2(2m_2).$$

Therefore,  $I(t)$  can be rewritten as

$$I(t) = A + B \left[ \cos(\Omega t) + \frac{1}{9} \cos(3\Omega t) \right], \tag{9}$$

where

$$\begin{cases} A = \frac{GE_0^2}{8t_{ff}} - \frac{GE_0^2}{16t_{ff}} [J_0(2m_1) + J_0(2m_2)], \\ B = -\frac{GE_0^2}{8t_{ff}} J_2(2m_1), \end{cases}$$

and

$$\Omega = 2 \left( \omega + \lim_{t \rightarrow 0} \frac{d\theta(t)}{dt} \right).$$

Then compare Eq. (9) with the Fourier expansion of a typical triangular waveform

$$\begin{aligned} T(t) &= C + D \left[ \cos(\Omega t) + \frac{1}{9} \cos(3\Omega t) + \frac{1}{25} \cos(5\Omega t) + \dots \right]. \tag{10} \end{aligned}$$

Considering that  $C$  and  $D$  are constant and the higher harmonics cannot make a significant contribution to the final waveform, so the triangular pulses could be obtained.

In addition, it should be noted that the method using single-stage drive MZM in Ref. [26] can generate versatile waveform optical pulses. It has tunable capability of both repetition rate and center wavelength. With the same driving signal applied, using the single-stage MZM can generate signal with the same frequency as the driving signal, whereas, using the dual-parallel MZM can generate signal with frequency three times to the driving signal.

### 3 Conclusions

By making comparison among the several schemes reviewed above, it can be obtained that the schemes using the CW laser as the source have obvious advantages over those using the MLL, noting that the CW laser provides more flexible operation, relatively wider tunability and higher stability than those of the MLL. In addition, CW laser is low-priced and simple. Therefore, the schemes using both the CW laser and the EO modulator will be the most promising candidate in generating the triangular-shaped pulses, just as the method proposed in Ref. [24]. But this scheme also has some shortages, it requires not only large modulation index (about 166%), but also great sensitivity of the phase shift operation (as referred before RF signals can be adjusted by the RF attenuator and the tunable delay line). The large modulation index means large amplification factor of the electrical amplifier, and good performance of the modulator. In addition, the sensitive phase shift makes it difficult to change the repetition rate of the pulse. Moreover, the triangular-shaped pulses generated in the scheme have a strong direct component in the time domain. Strictly speaking, it should be called the signals triangular-shaped waveform instead of triangular-shaped pulses. Despite the scheme in Ref. [24] is not perfect, it showed a meaningful way to generate the triangular-shaped pulses by using CW light. With the rapid development of optical fiber and semiconductor laser source, and the increasing applications for signal processing, such as shaping and filtering, much more systems will be developed for better function in photonic generation of the optical triangular-shaped pulses.

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