Triangular Pulse Generation by Polarization Multiplexed Optoelectronic Oscillator

Fangzheng Zhang, *Member, IEEE*, Bindong Gao, Pei Zhou, and Shilong Pan, *Senior Member, IEEE*

***Abstract*— A novel triangular pulse generator is proposed based on a polarization multiplexed optoelectronic oscillator (OEO). Employing a dual-polarization modulator, the proposed OEO can simultaneously oscillate at two frequencies of f and $3f$ along the two orthogonal polarizations of the same optical carrier. Thanks to the harmonic injection coupling between the two OEO oscillations, the generated two signals have an exact frequency ratio of 1:3 and can be tuned to be in phase with each other. By properly setting the amplitudes of the two signals, a triangular pulse train can be generated. The generation of a 4.44-GHz triangular pulse train is experimentally demonstrated. A very clean electrical spectrum incorporating the 4.44- and 13.32-GHz components is obtained, and the two tones have good phase noises of −100.6 dBc/Hz at 10 kHz and −99.2 dBc/Hz at 10 kHz, respectively. The generated triangular waveform is very close to an ideal waveform, and the root-mean-square error between the generated and the ideal waveforms is 5.145×10^{-4}.**

***Index Terms*— Microwave photonics, optoelectronic oscillator, triangular pulse generation, polarization multiplexing.**

I. Introduction

PHOTONIC generation of triangular-shaped waveform is an attractive research aspect, because triangular pulses have wide applications in optical signal processing techniques such as all-optical frequency conversion, doubling of optical pulses and optical pulse compression [1], [2], etc. Up to now, many approaches have been proposed for triangular-shaped pulse generation in the optical domain [3]–[13]. A method is based on spectrum shaping of an ultra-short pulse train followed by frequency to time mapping in a dispersion element [3]. In such system, the use of ultra-short pulses leads to a high cost and the generated triangular pulse usually has a small duty cycle (<1). To generate triangular pulses with a full duty cycle ($=1$), many schemes have been proposed based on external modulation of a continuous wave (CW) light. The basic principle is to generate two frequency harmonics, i.e., the 1st-order and 3rd–order harmonics, in the spectral domain. When the amplitude ratio between the two harmonics is nine, a temporal waveform approximate to triangular pulses can be generated. Based on this principle, a single dual-parallel Mach-Zehnder modulator (DPMZM) can be used to generate triangular pulses [4], [5]. Other electro-optical modulators can also be applied, but an assistant optical spectral processing model should be employed. For example, a Mach-Zehnder modulator (MZM) with an optical interleaver or a microwave photonic filter were employed in [6] and [7], respectively. In [8], a dual-electrode MZM with a span of fiber was used to generate triangular pulses. A polarization modulator placed inside a Sagnac loop was also proposed to generate triangular pulses in [9]. Besides, an MZM followed by optical sideband manipulation based on stimulated Brillouin scattering (SBS) effect was demonstrated for triangular pulse generation [10], [11]. A common property with these schemes is the requirement for an external microwave reference source that is applied to drive the electro-optical modulators. Recently, triangular pulse generation based on optoelectronic oscillators (OEO) was proposed [12], [13]. In such systems, the fundamental harmonic corresponding to the repetition rate of the triangular pulse train is generated by the OEO, thus the use of an external microwave source is avoided. Since the 3rd-order harmonic is generated by nonlinear electro-optical modulations, a large OEO loop gain is required and the loop gain should be very strictly controlled to achieve a precise amplitude ratio of 9:1 between the two harmonics.

In this letter, we propose and experimentally demonstrate a triangular pulse generation scheme based on a polarization multiplexed OEO. The proposed OEO can simultaneously oscillate at two different frequencies along two orthogonal polarizations of the same optical carrier. Because of the harmonic injection coupling between the two OEO oscillations, the two oscillating signals can have an exact frequency ratio of 1:3 and can be tuned to be in phase with each other. When the amplitude ratio between the two signals is set to 9:1, a triangular pulse train can be generated in time domain. To the best of our knowledge, this is the first report of a polarization multiplexed OEO and its application for triangular-shaped waveform generation. Since the two frequencies are generated by OEO oscillations along two orthogonal polarizations, the

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F. Zhang is with the Key Laboratory of Radar Imaging and Microwave Photonics Ministry of Education, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China, and also with the Science and Technology on Monolithic Integrated Circuits and Modules Laboratory, Nanjing 210016, China.

B. Gao, P. Zhou, and S. Pan are with the Key Laboratory of Radar Imaging and Microwave Photonics Ministry of Education, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China (e-mail: pans@ieee.org).

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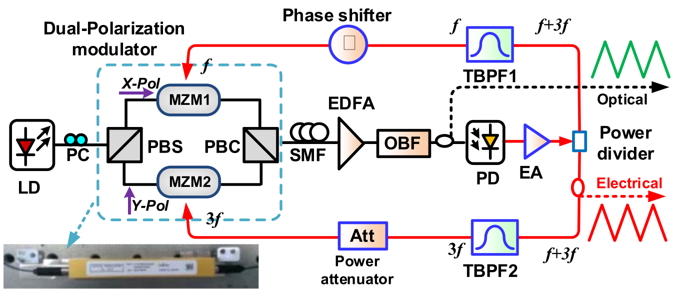

Fig. 1. The schematic diagram of the proposed triangular pulse generator. LD: laser diode; PBS: polarization beam splitter; PBC: polarization beam combiner; MZM: Mach-Zendher modulator; SMF: signal mode fiber; EDFA: erbium doped fiber amplifier; OBF: optical band-pass filter; PD: photodetector; EA: electrical amplifier; TBPF: electrical tunable band-pass filter.

undesired harmonics due to intermodulation can be effectively suppressed, which is helpful to generate high quality triangular pulses.

II. Principle

Figure 1 shows the schematic diagram of the proposed triangular pulse generator. The key component is a commercial dual-polarization modulator which is initially designed to generate polarization multiplexed optical signals in coherent optical communication systems [14]. The dual-polarization modulator can be considered to be composed by a polarization beam splitter (PBS), two MZMs (MZM1 and MZM2), and a polarization beam combiner (PBC), as shown in Fig. 1. The CW light generated from a laser diode (LD) is directed to the modulator via a polarization controller (PC). By adjusting the PC to let the polarization state of the input light have an angle of 45° to one principal axis of the PBS inside the modulator, the CW light is equally split into two branches in two orthogonal polarizations (i.e., X and Y) after the PBS. Then, the light in each polarization is modulated by MZM1 and MZM2, respectively, before they are combined at the PBC. After the modulator, the polarization multiplexed signal passes through a span of single mode fiber (SMF). To boost the optical power, an erbium doped fiber amplifier (EDFA) can be applied after the SMF, and an optical band-pass filter (OBF) is followed to suppress the amplified spontaneous emission (ASE) noise. After the OBF, the optical signal is sent to a PD to realize optical-to-electrical conversion. The electrical signal from the PD is properly amplified by an electrical amplifier (EA) and then split into two branches by an electrical power divider. The electrical signal in each branch passes through an electrical tunable band-pass filter (TBPF1 and TBPF2), respectively. The center frequencies of the two TBPFs are f and $3f$. After the filters, the signals at f and $3f$ are fed back to drive the two MZMs, respectively. To this point, two OEO loops are constructed along the two orthogonal polarizations of the same laser source. After the oscillation at f is established in the upper OEO loop, the small 3^{rd}-order harmonic at $3f$ generated by nonlinear modulation at MZM1 is injected to the lower OEO loop. When the injection frequency is close to one of the free-running oscillation modes of the lower OEO loop, an injection-locked oscillation at $3f$ can be achieved in the lower OEO. Using a phase shifter in the upper OEO loop to slightly adjust the oscillation frequency (f) [15], the injection frequency ($3f$) will change slightly. According to the injection locking properties [16], when the injection frequency deviates from the free-running oscillation mode of the lower OEO loop, to maintain a stable oscillation at $3f$, the phase of the oscillation signal would change such that the vector sum of the oscillation signal and the injection signal can achieve a round-trip phase shift of $2n\pi$ (n is an integer). Therefore, by slightly adjusting the injection frequency within the injection-locking range, the phase difference between the final oscillation signal and the injection signal can be tuned. Based on this principle, the signals generated by the two OEO loops can be tuned to be in phase with each other. By further using an electrical attenuator to control the amplitude of the signal in the lower OEO, the generated frequency components at f and $3f$ can have an amplitude ratio of 9:1. The combined electrical signal can be expressed as

$$S(t) \propto DC + \cos(2\pi f t) + \frac{1}{9}\cos(6\pi f t) \qquad (1)$$

which corresponds to a triangular pulse train in time domain when only the 1^{st}- and 3^{rd}-order harmonics are considered.

In the proposed system, MZM1 is biased at the quadrature point, thus the even-order harmonics are suppressed in the upper OEO loop. Besides, because the photonic detections of optical signals along two orthogonal polarizations have no interference with each other, the intermodulation between the generated frequency components at f and $3f$ can be effectively suppressed in the proposed OEO, which also helps to obtain a clean spectrum including only the 1st- and 3rd-order harmonics. The harmonic injection coupling between the two OEO loops can ensure the generated signals have an exact frequency ratio of 1:3. Since a small signal injection is needed in the proposed method, the OEO loop gain can be reduced compared with the previous OEO-based schemes where a large loop gain is required to generate the 3^{rd}-order harmonic by nonlinear electro-optical modulation. Accordingly, the requirement for high power electrical/optical devices (e.g., the PD and amplifier) is relaxed.

III. Experiment Results and Discussion

An experiment is carried out to verify the feasibility of the proposed triangular pulse generator. In the experiment, a CW light at 1550.51 nm is generated from an LD (TeraXion NLL04) with a power of 13 dBm. The modulator is a dual-polarization BPSK (DP-BPSK) $LiNbO_3$ modulator (Fujitsu FTM7980EDA) which has a 3-dB bandwidth of ~30 GHz and a half-wave voltage of 3.5 V@ 21.5 GHz for each MZM. The two MZMs are both biased at the quadrature point. The SMF in the OEO has a length of 0.4 km. To compensate for the optical power loss due to the modulator (~11 dB) and the SMF, an EDFA is applied after the SMF. Following the EDFA, an OBF (Yenista XTM-50) is connected to suppress the ASE noise. The filtered optical

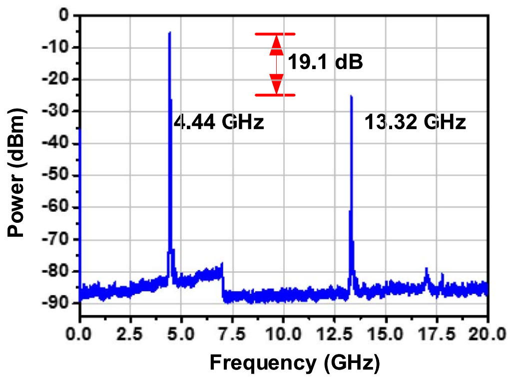

Fig. 2. Measured electrical spectrum with 4.44- and 13.32-GHz components.

signal is sent to a PD, which has a bandwidth of 18 GHz and a responsivity of 0.65 A/W. The electrical signal from the PD is first amplified by an electrical amplifier (EA) with a gain of ~30 dB. The amplified electrical signal is then split into two branches by a power divider. The two TBPFs both have a 3-dB bandwidth of ~50 MHz, and their central frequencies can be tuned in 4-8 GHz, and 8-13.6 GHz, respectively. After passing the two electrical signals through an electrical phase shifter and a power attenuator, respectively, the two signals are fed to the RF ports of the dual-polarization modulator, and two OEO loops are completed. To monitor the optical and electrical signals, a 10-dB optical coupler and a 3-dB electrical coupler are placed before the PD and after the electrical power divider, respectively. The small portion (10%) of the optical signal is analyzed by an optical spectrum analyzer (OSA) and an 80 GHz sampling oscilloscope (OSC, Agilent, 86100C) which has an optical waveform measurement model. The electrical spectrum and waveform is observed by an electrical spectrum analyzer (ESA, R&S FSV40) with a phase noise measurement model and the OSC, respectively.

By properly adjusting the loop gain, the TBPFs and the phase shifter, two oscillating frequencies at $f = 4.44$ GHz and $3f = 13.32$ GHz are generated. By tuning the electrical power attenuator, the power difference between the two frequencies is controlled to be 19.1 dB, which corresponds to an amplitude ratio very close to 9 between the 4.44 GHz and 13.32 GHz components. Fig. 2 shows the electrical spectrum of the generated two-tone signal. As can be seen, the spectrum is very clean without apparent even-order harmonics. To evaluate the quality of the two oscillating frequencies, phase noise of the two frequency components is investigated. Fig. 3(a) and (b) shows the measured phase noise of the 4.44 GHz and 13.32 GHz signals, respectively. The insets in Fig. 3 are the electrical spectra in a 200-kHz span (the resolution bandwidth is 1 kHz). It is found that, the phase noise at 10 kHz offset is −100.6 dBc/Hz and −99.2 dBc/Hz for the 4.44 GHz and 13.32 GHz signals, respectively. Here, the phase noise of the 1st-order harmonic is similar to that in [13] and a little worse than that in [12]. Due to the relatively large bandwidth of the TBPFs (~50 MHz@ 3dB), side modes still exist in the electrical spectrum. The side mode suppression

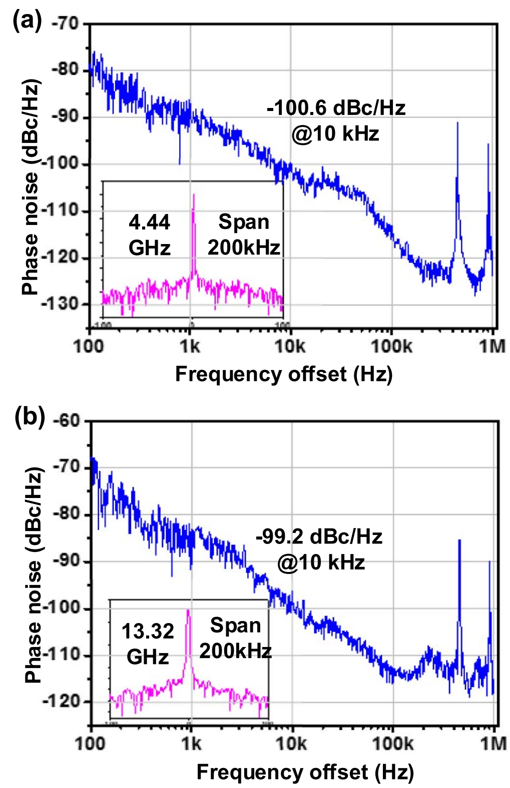

Fig. 3. (a) Measured phase noise of the 4.44 GHz signal, and (b) measured phase noise of the 13.32 GHz single. Insets: electrical spectrum of the 4.44 GHz and 13.32 GHz signals in a 200 kHz span (RBW: 1 kHz).

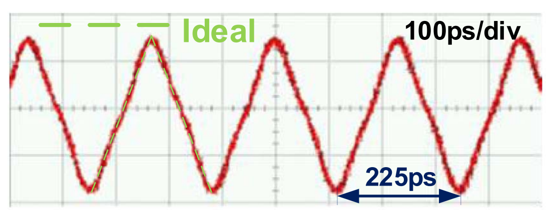

Fig. 4. Measured waveform of the triangular pulse train at the electrical output.

ratio is measured to be 50 dB, which can be increased by applying TBPFs with smaller bandwidth.

Figure 4 shows the waveform of the generated 4.44 GHz electrical triangular pulse train measured by the OSC. It is found that, the waveform is very close to an ideal triangular pulse shape. Mathematically, the root mean square error (RMSE) between the generated and the ideal triangular waveforms is calculated to be 5.145×10^{-4}, which is better than the results in [12] and [13]. Considering the phase noise of the 1st-order harmonic has no advantage over with the previous works, the smaller RMSE is attributed to the precise amplitude ratio between the two harmonics and the clean spectrum without undesired frequency components. When using a longer SMF (1 km) in the established OEO, the phase noise can be slightly improved, while the temporal properties of the triangular pulses are nearly unchanged.

The optical signal exported before the PD is also analyzed. Fig. 5(a) shows the optical spectrum measured with

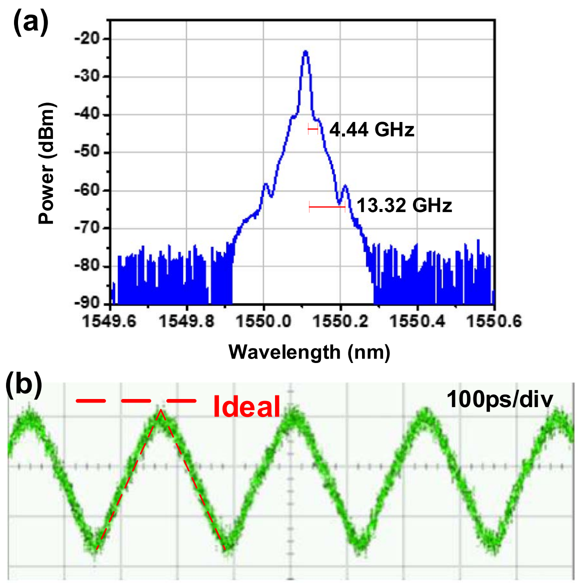

Fig. 5. (a) Measured optical spectrum of the signal before the PD, and (b) the measured optical triangular waveform.

a resolution of 0.02 nm. As can be observed, two pairs of optical sidebands separated from the carrier by 4.44 GHz and 13.32 GHz are generated. It should be noted that, the two pairs of sidebands are located along the two orthogonal polarization states. When this optical signal is sent to the optical port of the OSC, the observed triangular pulses are shown in Fig. 5(b), which is also very close to the ideal triangular pulses.

The oscillating frequency of an OEO can be changed by tuning the pass-band of the TBPF, thus the repetition rate of the generated triangular pulse can also be adjusted. In the experiment, due to the limited tuning range of the two TBPFs, the repetition rate tunability is not demonstrated. A potential problem associated with the repetition rate tunability is that two TBPFs and a phase shifter should be tuned all together, which may increase the complexity and limit the tuning-speed. A possible solution for this problem is to apply novel microwave photonic filters, as demonstrated in [12].

IV. Conclusion

We have proposed and demonstrated a scheme for full-duty cycle triangular pulses generation by using a polarization multiplexed OEO. The triangular pulse is obtained by generating two oscillating frequencies in the proposed OEO, without the use of external microwave sources. Feasibility of the proposed signal generator is verified by the generation of a 4.44 GHz triangular pulse train. Clean spectrum incorporating only the 1st- and 3rd-order harmonics are observed, and good phase noise is achieved for both of the two harmonics. The RMSE between the generated waveform and the ideal triangular waveform is as small as 5.145×10^{-4}, which verifies the good quality of the generated triangular pulses.

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