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A Simple Technique for Triangular Waveform Generation based on a Dual-Polarisation Modulator

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Abstract: A new microwave photonic topology for generating a triangular waveform is presented. The concept is based on incoherent summation of two intensity modulated optical signals to generate the first and third order harmonic frequency components with the same amplitude and phase as that of an ideal triangular waveform. The proposed triangular waveform generator has a very simple and low-cost structure as it only requires the Mach Zehnder modulator in a conventional fibre optic link to be replaced by an integrated dual-polarisation modulator driven by two 90° phase difference RF signals. It also has a widely tunable repetition rate, low insertion loss and a stable performance. Experimental results demonstrate a triangular waveform with a tunable microwave-frequency repetition rate and a root mean square error value of < 0.049 when comparing with an ideal triangular waveform. The stability of the proposed triangular waveform generator is also examined experimentally.

Index Terms: Fiber optics communications, radio frequency photonics, waveform generation, triangular pulses.

1. Introduction

Recently there has been a growing interest in using microwave photonic techniques for generating arbitrary waveforms. The reason behind this is that microwave photonic waveform generators have the ability to generate an arbitrary waveform with a high frequency and a large bandwidth that cannot be obtained using electronic techniques. Furthermore, electronic waveform generators have issues such as high timing jitter, susceptibility to electromagnetic interference, high loss and large size [1]. Among various waveforms, a triangular waveform has a number of applications including signal processing and communication system engineering [2]. For example, it is used in the frequency modulated continuous waveform (FMCW) radar for multi-target detection in vehicular applications [3].

A triangular waveform can be generated using a frequency-to-time mapping technique [4]. This technique relies on using a pulsed laser source and optical filters to shape the optical pulse train to have a triangular shape. The demerits of this technique are high cost due to the need of an ultra-short optical pulse source, limited repetition rate tunability caused by the dispersive element used in the setup, and a small duty cycle. A triangular waveform can be obtained by generating an electrical spectrum consists of odd order harmonics of the waveform repetition rate with specific amplitude and phase relationship that matches with the frequency components of an ideal triangular waveform. Simulation results show a triangular waveform generated by using only the first and third order harmonics of an ideal triangular waveform has a root mean square error (RMSE) value of 0.0279 when comparing with an ideal triangular waveform [5]. There are two common ways to generate the first and third order harmonics. One is based on using an optoelectronic oscillator, which has the advantage of no external microwave

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reference source is needed [6], [7]. However, the setup involves a number of electrical components such as tunable bandpass filters, an amplifier, a phase shifter and a variable attenuator. This increases the system size and limits the repetition rate of the generated triangular waveform. Furthermore, various system parameters need to be adjusted in order to tune the repetition rate and the repetition rate cannot be tuned continuously. Another way is based on external modulation of a continuous wave optical carrier using an RF signal. Various structures [5], [8]-[16] have been reported using this technique for generating a triangular waveform. Almost all of these reported structures require components in addition to a laser source, an optical modulator and a photodetector in a conventional fibre optic link. For example a structure based on a dual-parallel modulator requires an electrical frequency tripler [8], which limits the repetition rate and increases the system insertion loss, a structure based on an optical phase modulator inside a Sagnac loop interferometer requires a tunable dispersion compensation module and polarisation rotators [10], which has stability problem as light polarisation state is sensitive to changes in environmental condition, and structures based on stimulated Brillouin scattering require an optical frequency shifter and a highly nonlinear fibre [10], [11]. The use of additional components in a fibre optic link to generate a triangular waveform increases the system complexity, size and cost, as well as the insertion loss. Triangular waveform generators based on using an optical filter to control the modulation sideband amplitudes [12], [13] and based on a microwave photonic filter to control the harmonic amplitudes [14], limit the triangular waveform repetition rate tunability. Until now, the simplest microwave photonics approach to generate a triangular waveform is based on a dual-parallel modulator driven by two 90° phase difference RF signals [15].

In this paper, we present a triangular waveform generator that has a simpler structure and a simpler operating principle than the one presented in [15]. It is based on an integrated dual-polarisation modulator, which only requires two bias voltages rather than three in a dual-parallel modulator. Hence it is less susceptible to the modulator bias drift. The dual-polarisation modulator based triangular waveform generator does not require additional components other than replacing the Mach Zehnder modulator (MZM) by a dual-polarisation modulator with a 90° hybrid coupler connected to the modulator input, in a fibre optic link. Unlike a dual-parallel modulator, the two intensity modulated optical signals at the output of a dual-polarisation modulator are combined incoherently at the photodetector. A technique to overcome the phase imbalance in the 90° hybrid coupler causing degradation in the triangular waveform is also presented. The proposed triangular waveform generator is analysed and demonstrated experimentally.

2. Operation Principle and Analysis

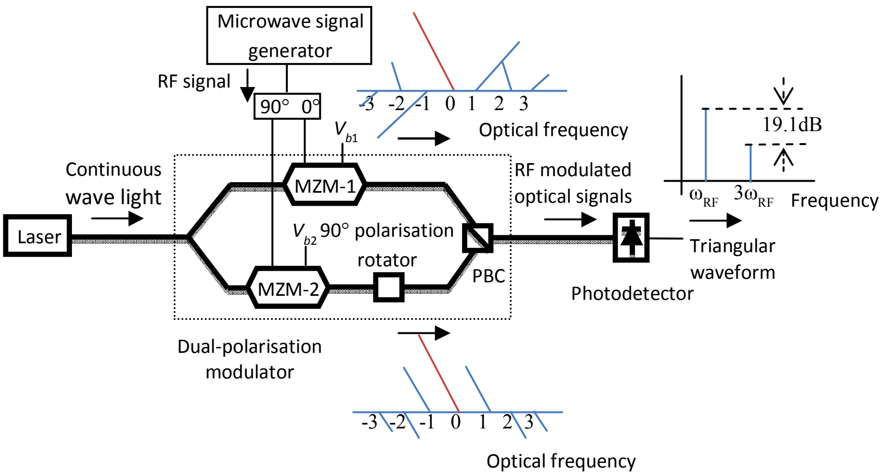

Fig. 1. Dual-polarisation modulator based triangular waveform generator.

The schematic diagram of the new triangular waveform generator is shown in Fig. 1. The key component in the structure is the dual-polarisation modulator, which consists of a 3 dB optical coupler, two MZMs (MZM-1 and MZM-2), a 90° polarisation rotator and a polarisation beam combiner (PBC) integrated on the same substrate. A continuous wave light from an optical source travelling in the slow axis of a fibre is equally split into two at the 3 dB coupler inside the dual-polarisation modulator. The light is intensity modulated by an RF signal with an angular frequency ω_{RF} into the MZMs. The polarisation rotator at the output of the bottom MZM rotates the polarisation state of the intensity modulated optical signal travelled in the bottom path by 90°. The two intensity modulated optical signals in the top and bottom path of the integrated dual-polarisation modulator are combined at the PBC and then detected by a photodetector.

Since the two intensity modulated optical signals at the output of the integrated dual-polarisation modulator have an orthogonal polarisation state, they are combined incoherently at the photodetector and hence the triangular waveform generator shown in Fig. 1 can be analysed using the MZM transfer function. The structure of the dual-polarisation modulator based triangular waveform generator is simpler compared to the previously reported triangular waveform generators [5], [8]-[16], which involve additional components in a fibre optic link. The analysis of the proposed structure is also simple as it does not involve optical carrier and RF modulation sideband electric fields. The power of the two orthogonally polarised intensity modulated optical signals before the photodetector can be expressed as

$$P_{o1} = \frac{t_{ff} P_{in}}{4}\left(1+\cos\frac{\pi}{V_\pi}\left(V_{RF1}\sin(\omega_{RF}t)+V_{b1}\right)\right) \tag{1}$$

$$P_{o2} = \frac{t_{ff} P_{in}}{4}\left(1+\cos\frac{\pi}{V_\pi}\left(V_{RF2}\sin(\omega_{RF}t+\phi)+V_{b2}\right)\right) \tag{2}$$

where t_{ff} is the MZM insertion loss, P_{in} is the optical power of the continuous wave light into the dual-polarisation modulator, V_{RF1} and V_{RF2} are the amplitudes of the RF signal into MZM-1 and MZM-2 respectively, V_π is the MZM switching voltage, ϕ is the phase difference between the two RF signals into the two MZMs, and V_{b1} and V_{b2} are MZM-1 and MZM-2 bias voltage respectively. The current at the photodetector output is the product of the photodetector responsivity $\Re$ and the sum of the two intensity modulated optical signal powers. It is given by

$$I = \frac{\Re t_{ff} P_{in}}{4}\left[2+\cos\frac{\pi}{V_\pi}\left(V_{RF1}\sin(\omega_{RF}t)+V_{b1}\right)+\cos\frac{\pi}{V_\pi}\left(V_{RF2}\sin(\omega_{RF}t+\phi)+V_{b2}\right)\right] \tag{3}$$

The photocurrent at the k^{th} order harmonic frequency is obtained by collecting the terms that contain k times the input RF signal angular frequency, i.e. $k{\cdot}\omega_{RF}$, from (3). Hence the photocurrents at the odd order harmonic frequencies of the input RF signal can be written as

$$I_{m=1,3,5,\ldots} = \frac{-\Re t_{ff} P_{in}}{4}\sqrt{A_m^2+B_m^2}\,\sin\left(m\omega_{RF}t+\tan^{-1}\left(\frac{B_m}{A_m}\right)\right) \tag{4}$$

where

$$A_m = 2J_m(\beta_{RF1})\sin(\beta_{b1})+2J_m(\beta_{RF2})\cos(m\phi)\sin(\beta_{b2}) \tag{5}$$

$$B_m = 2J_m(\beta_{RF2})\sin(m\phi)\sin(\beta_{b2}) \tag{6}$$

where $J_k(x)$ is the Bessel function of k^{th} order of first kind, $\beta_{b1}=(\pi V_{b1})/V_\pi$ and $\beta_{b2}=(\pi V_{b2})/V_\pi$, and $\beta_{RF1}=(\pi V_{RF1})/V_\pi$ and $\beta_{RF2}=(\pi V_{RF2})/V_\pi$ are the modulation index of MZM-1 and MZM-2 respectively. Similarly the photocurrent at the even order harmonic frequencies can be written as

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$$I_{n=2,4,6,\ldots} = \frac{\Re t_{ff} P_{in}}{4}\sqrt{C_n^2 + D_n^2}\cos\left(n\omega_{RF}t + \tan^{-1}\left(\frac{D_n}{C_n}\right)\right) \tag{7}$$

where

$$C_n = 2J_n(\beta_{RF1})\cos(\beta_{b1}) + 2J_n(\beta_{RF2})\cos(n\phi)\cos(\beta_{b2}) \tag{8}$$

$$D_n = 2J_n(\beta_{RF2})\sin(n\phi)\cos(\beta_{b2}) \tag{9}$$

The electrical power of the odd and even order harmonic frequency components are given by

$$P_{m,out} = \frac{1}{2} I_m^2 R_o \tag{10}$$

$$P_{n,out} = \frac{1}{2} I_n^2 R_o \tag{11}$$

where R_o is the photodetector load resistance.

The parameters that can be adjusted in the proposed structure are the modulation indexes β_{RF1} and β_{RF2}, the phase difference between the two RF signals into the MZMs ϕ, and the modulator bias β_{b1} and β_{b2}. It is well known that an ideal triangular waveform has no even order harmonics. According to (7)-(9), the even order harmonics at the output of the proposed structure can be cancelled by biasing the two MZMs at the quadrature point. The amplitude and phase relationship of the photocurrents at the odd order harmonic frequencies need to match with that given in the Fourier series expansion of an ideal triangular waveform, which is given by [5]

$$T_{tr}(t) = C_{tr} + D_{tr}\sum_{k=1,3,5,\ldots}^{\infty} \frac{1}{k^2}\cos(k\omega_m t + \theta_k) \tag{12}$$

where C_{tr} and D_{tr} are constant, which determine the average amplitude and the peak amplitude of the triangular waveform respectively, and θ_k is the phase of the k^{th} order harmonics. Various k^{th} order harmonic phase settings such as θ_k=0° [5], θ_k=k×90° [9], or θ_k=k×45° [15] can be used to generate a triangular waveform. The difference between them is the generated triangular waveforms have different phases. The RF signals into the two MZMs inside the dual-polarisation modulator were designed to have a 90° phase difference so that the phase of the 1st and 3rd order harmonic are -45° and -135° respectively in order to satisfy the phase requirement for generating a triangular waveform. The amplitudes of the two RF signals were designed so that the MZMs inside the dual-polarisation modulator have the same modulation index β_{RF1}=β_{RF2}=1.51 to obtain a 1/9 photocurrent amplitude ratio at the 1st and 3rd order harmonic frequencies or 19.1 dB electrical power difference between the 1st and 3rd order harmonics. Fig. 2 shows the simulated waveform generated by the dual-polarisation modulator based triangular waveform generator. An ideal triangular waveform obtained by using 25 odd order harmonics, i.e. k=1, 3, 5, …, 50, in (12), is also shown in the figure for comparison. A RMSE value of 0.0275 was obtained from the two waveforms shown in Fig. 2 and is agreed with the RMSE value given in [5].

A 90° hybrid coupler can be used to split an RF signal into two with a 90° phase difference in the dual-polarisation modulator based triangular waveform generator. Broadband 90° hybrid couplers are commercially available. However, they have phase imbalance, i.e. the phase difference between the two coupler outputs is not exactly 90° and this phase difference is frequency dependent. For example, a 90° hybrid coupler with a 3 dB bandwidth of 4-40 GHz from Marki Microwave has a typical phase imbalance of ±5°. The phase imbalance from the 90° hybrid coupler causes the 1st and 3rd order harmonic amplitude ratio deviates from 1/9, which in turn alters the shape of the generated triangular

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waveform. This problem can be overcome by adjusting the modulation index via controlling the power of the RF signal into the modulators. This is because the photocurrents at the 1st and 3rd order harmonic frequency are dependent on both the modulation index and the phase difference between the two RF signals into the two MZMs. The modulation index required to compensate for the effect of the 90° hybrid coupler phase imbalance to maintain the 1/9 amplitude ratio for the 1st and 3rd order harmonics can be obtained from (4)-(6) and is shown in Fig. 3.

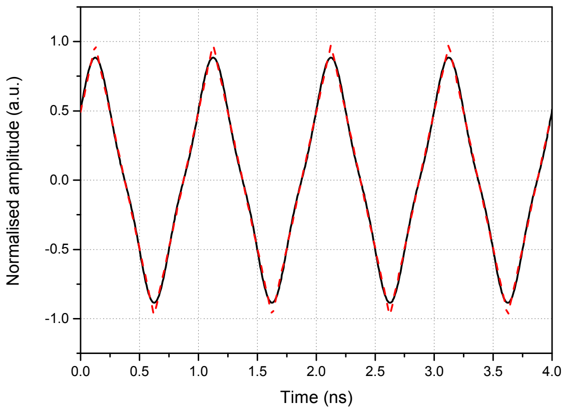

Fig. 2. Simulated waveform generated by the dual-polarisation modulator based triangular waveform generator (black solid line) and the ideal triangular waveform obtained using (12) with C_{tr}=0 and D_{tr}=5 (red dashed line).

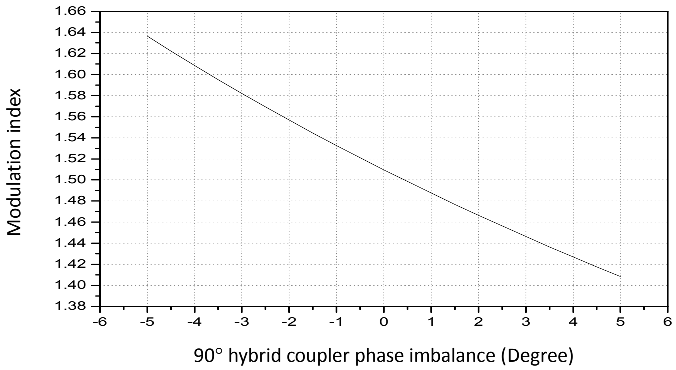

Fig. 3. Modulation index required to maintain 19.1 dB power difference between the 1st and 3rd order harmonics versus 90° hybrid coupler phase imbalance.

In practice, MZMs suffer from the bias drift problem. The effect of the modulator bias drift to the generated triangular waveform was investigated. The RMSE value obtained from the waveform generated by the proposed structure and the ideal triangular waveform versus the percentage of bias drift in the two MZMs inside the dual-polarisation modulator is shown in Fig. 4. It can be seen that a ±15% modulator bias drift, which corresponds to ±0.3 V changes in the modulator DC bias voltage of 2 V, causes only 0.004 changes in the RMSE value. This indicates that the performance of the proposed triangular waveform generator is not sensitive to the modulator bias drift. The RMSE value for changes in the modulation index of one of the MZMs in the dual-polarisation modulator based triangular waveform generator was also simulated. The simulation result shows a ±10% change in MZM-2 modulation index causes < 0.007 changes in the RMSE value.

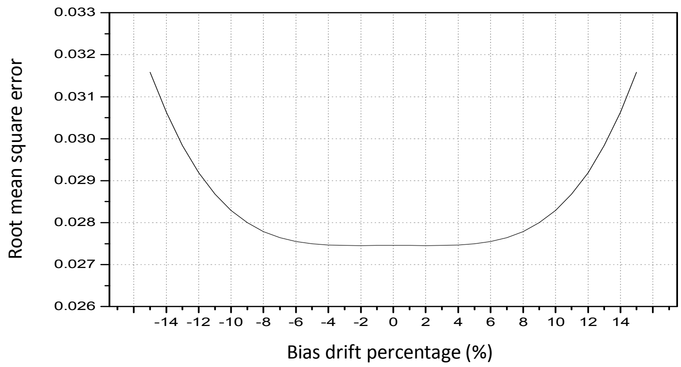

Fig. 4. Variation in RMSE value obtained by comparing the waveform generated by the dual-polarisation modulator based triangular waveform generator with the ideal triangular waveform versus the percentage of bias drift in the dual-polarisation modulator.

The dual-polarisation modulator based triangular waveform generator has a very simple and low-cost structure. It only requires the intensity modulator in a conventional fibre optic link to be replaced by a dual-polarisation modulator driven by two 90° phase difference RF signals, and only two DC bias voltages are needed for the dual-polarisation modulator. The dual-polarisation modulator consists of two MZMs, which can be made to have a wide bandwidth, and broadband 8-67 GHz 90° hybrid couplers are commercially available. Hence a triangular waveform with a high repetition rate of > 20 GHz can be generated by the proposed structure. Furthermore, the repetition rate of the proposed triangular waveform generator can easily be tuned via changing the input RF signal frequency whereas the structures presented in [9], [11], [13] require controlling either the dispersive element dispersion, the pump light frequency or the optical filter bandwidth, to tune the waveform repetition rate. The 1st order harmonic at the output of the proposed triangular waveform generator is only around 7 dB lower than that of a conventional fibre optic link formed by a laser source, a MZM and a photodetector. This indicates that the proposed structure has a low insertion loss. It is worth to point out that the structure shown in Fig. 1 can be used to generate a three-harmonic sawtooth waveform and a two-harmonic square waveform by designing the system parameters β_{RF1}, β_{RF2}, ϕ, β_{b1} and β_{b2} therefore it has the same function as the waveform generator presented in [5]. It should be pointed out that a triangular waveform generator implemented by a dual-polarisation modulator has been reported [16]. However, it requires an electrical frequency tripler at the modulator input, which limits the waveform generator operating frequency and increases the system insertion loss.

4. Experimental results

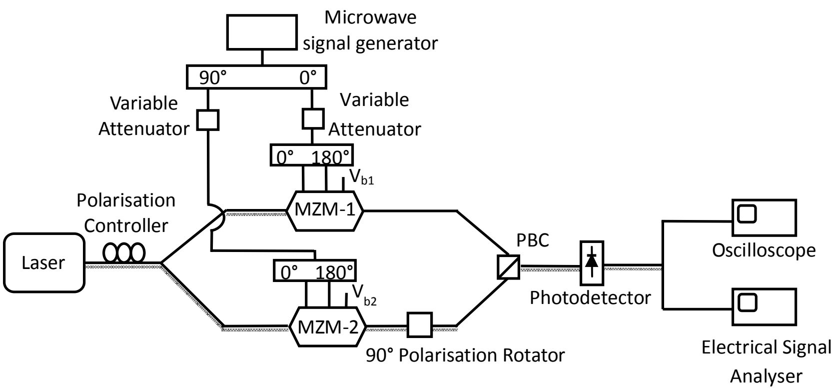

Fig. 5. Experimental setup of the dual-polarisation modulator based triangular waveform generator.

The triangular waveform generator was set up as shown in Fig. 5. A continuous wave light with 1550 nm wavelength and 13 dBm output power from a wavelength tunable laser (Santec WSL-100) passed through a polarisation controller into a dual-polarisation modulator (Fujitsu FTM7980EDA). Each MZM inside the dual-polarisation modulator had two RF input ports. The bandwidth and the switching voltage of the MZM were over 20 GHz and 3.5 V respectively. An RF signal from a microwave signal generator was split by a 90° hybrid coupler. Each output of the 90° hybrid coupler was connected to an electrical variable attenuator, a 180° hybrid coupler and the MZM inside the dual-polarisation modulator. The 180° hybrid coupler was used to split the RF signal into two with the same amplitude but an opposite phase before applying into the dual-drive MZM. In this case, the dual-drive MZM behaves like a standard single-drive MZM. The electrical variable attenuators were adjusted to compensate for the 90° hybrid coupler amplitude imbalance and different insertion losses at the inputs of the two MZMs to ensure the RF signals into the two MZMs have the same power. Hence the two MZMs inside the dual-polarisation modulator had the same modulation index. The output of the dual-polarisation modulator was detected by a photodiode (Discovery Semiconductor DSC30S).

The DC voltages into the dual-polarisation modulator were adjusted to bias the two MZMs at the quadrature point ($\beta_{b1}=\beta_{b2}=\pi/2$). This was done by applying the RF signal into MZM-1 only and adjusting the DC voltage into this MZM until the 2nd order harmonic at the output of the dual-polarisation modulator based triangular waveform generator was minimised. The same step was repeated for MZM-2. The power of the RF signal from the microwave signal generator was adjusted to ensure the power difference between the 1st and 3rd order harmonics was 19.1 dB. The output waveform was measured on a 6 GHz bandwidth oscilloscope (Keysight MSOX6004A) for an RF signal with a frequency of 1.6 GHz, 1.8 GHz and 2 GHz into the modulator. The measurements are shown in Fig. 6(a)-(c).

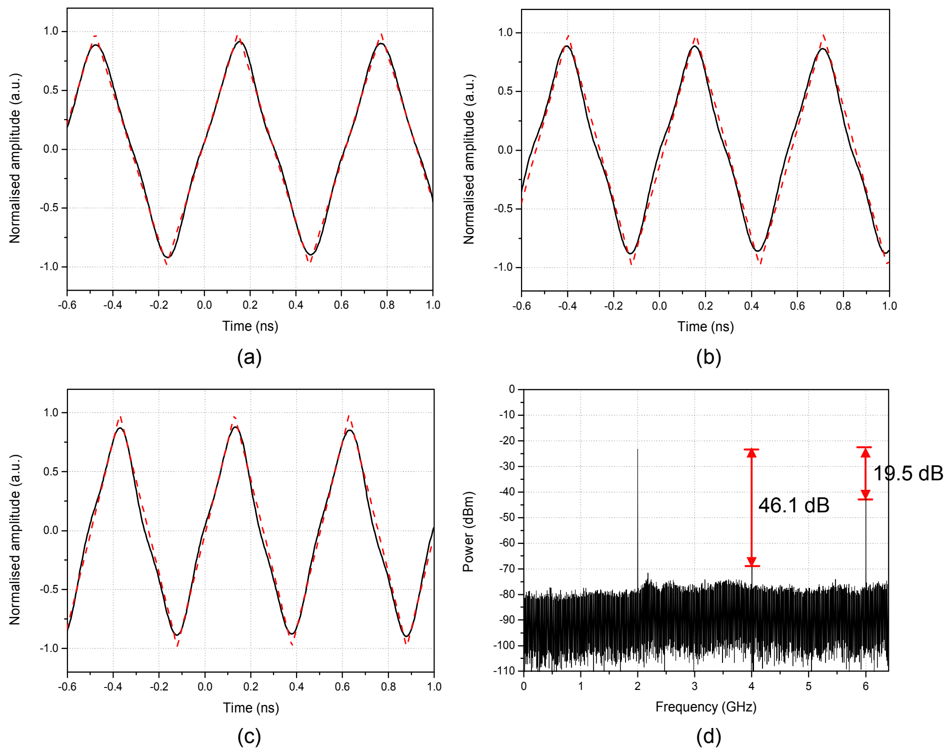

Fig. 6. Measured triangular waveform (black solid line) and simulated ideal triangular waveform (red dashed line) with (a) 1.6 GHz, (b) 1.8 GHz, and (c) 2 GHz repetition rate. (d) Measured electrical spectrum of the 2 GHz repetition rate triangular waveform. The electrical signal analyser resolution bandwidth is 100 kHz.

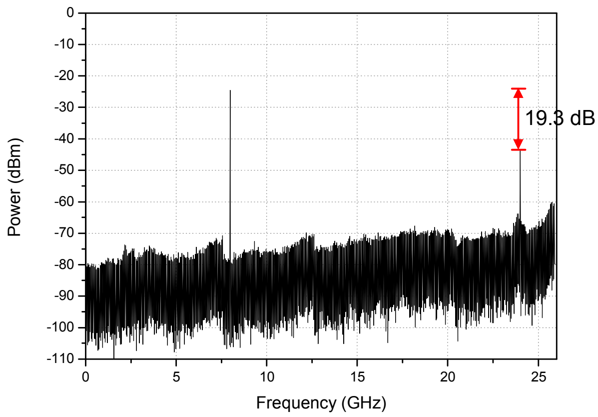

Fig. 7. Output electrical spectrum of the proposed triangular waveform generator for an 8 GHz RF signal into the modulator. The electrical signal analyser resolution bandwidth is 100 kHz.

An ideal triangular waveform is also shown in the figures for comparison. A small RMSE value of 0.0332, 0.0459 and 0.0483 were obtained from the measured waveforms shown in Fig. 6(a)-(c) when comparing with the ideal triangular waveforms. This demonstrates the proposed structure can generate a microwave-frequency triangular waveform with the shape close to an ideal triangular waveform and the waveform repetition rate can be tuned by controlling the input RF signal frequency. The output electrical spectrum of the 2 GHz triangular waveform shown in Fig. 6(c) was also measured on an electrical signal analyser (Keysight N9000A) and is shown in Fig. 6(d). It can be seen that the difference in the 1^{st} and 3^{rd} order harmonic power is 19.5 dB and the 2^{nd} order harmonic is > 26 dB below the 3^{rd} order harmonic.

Due to the oscilloscope used in the experiment has only 6 GHz bandwidth, a triangular waveform can only be measured up to 2 GHz to ensure both the 1^{st} and 3^{rd} order harmonics are within the oscilloscope bandwidth. Otherwise the waveform generated by the proposed structure will be distorted by the oscilloscope. In order to demonstrate the proposed structure can generate a triangular waveform with a frequency above 2 GHz, the dual-polarisation modulator based triangular waveform generator output electrical spectrum was measured for an 8 GHz RF signal into the modulator using the 26.5 GHz bandwidth electrical signal analyser. A power difference of 19.3 dB between the 1^{st} and 3^{rd} order harmonics and the 2^{nd} order harmonic below the system noise floor can be seen in Fig. 7. This demonstrates the setup can generate an 8 GHz triangular waveform. The repetition rate of the experimental setup was limited by the bandwidth of the dual-polarisation modulator and the photodiode used in the experiment, which were around 22 GHz, to avoid large suppression in the 3^{rd} order harmonic amplitude in order to obtain 1/9 amplitude ratio of the 1^{st} and 3^{rd} order harmonics. Finally, the stability of the dual-polarisation modulator based triangular waveform generator was examined. This was done by observing changes in the triangular waveform with 1.8 GHz repetition rate generated by the proposed structure over a period of time. Fig. 8 shows little changes in the measured waveform after one hour. The changes in the waveform are mainly caused by the modulator bias drift, which can be minimised by incorporating a bias controller in the setup.

5. Conclusion

A new microwave photonic triangular waveform generator has been presented. It has a very simple and low-cost structure. It is capable of realising a triangular waveform with a high repetition rate of > 20 GHz as MZMs [17] and 90° hybrid couplers [18] with an operating frequency of > 60 GHz are commercially available. Tuning the waveform repetition rate can be done by simply controlling the RF signal frequency into the modulator. A technique has been proposed to overcome the effect of phase imbalance in the 90° hybrid coupler used in the structure. The proposed triangular waveform generator has been analysed and the setting of the system parameters required to obtain a triangular waveform has been presented. Experimental results demonstrated the waveform generated by the proposed triangular waveform generator has a tunable microwave-frequency repetition rate, a small RMSE value of < 0.049 when comparing with the ideal triangular waveform, and a stable performance.

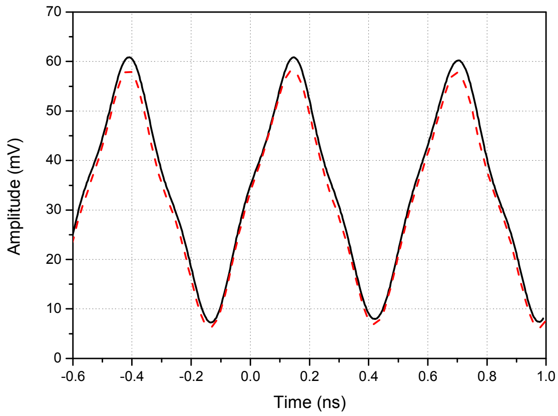

Fig. 8. Measured 1.8 GHz repetition rate triangular waveform (black solid line) and the waveform after one hour (red dashed line).

References

[1] A. Rashidinejad, Y. Li, and A. M. Weiner, "Recent advances in programmable photonic-assisted ultrabroadband radio-frequency arbitrary waveform generation," *IEEE Journal of Quantum Electronics*, vol. 52, no. 1, pp. 1-17, 2016.

[2] W. Y. Wang, W. Li, W. H. Sun, W. Wang, J. G. Liu, and N. H. Zhu, "Triangular microwave waveforms generation based on an optoelectronic oscillator," *IEEE Photon. Technol. Lett.*, vol. 27, no. 5, pp. 522-525, 2015.

[3] Y. Fan, Z. Yang, X. Bu, and J. An, "Radar waveform design and multi-target detection in vehicular applications," *2015 International Conference on Estimation, Detection and Information Fusion (ICEDIF)*, pp. 286-289, 2015.

[4] J. Ye, L. Yan, W. Pan, B. Luo, X. Zou, A. Yi, and S. Yao, "Photonic generation of triangular-shaped pulses based on frequency-to-time conversion," *Opt. Lett.*, vol. 36, no. 8, pp. 1458-1460, 2011.

[5] W. Li and J. Yao, "Photonic generation of microwave waveforms based on a polarization modulator in a Sagnac loop," *J. Lightwave Technol.*, vol. 32, no. 20, pp. 3637-3644, 2014.

[6] F. Zhang, B. Gao, P. Zhou, and S. Pan, "Triangular pulse generation by polarization multiplexed optoelectronic oscillator," *IEEE Photon. Technol. Lett.*, vol. 28, no. 15, pp. 1645-1648, 2016.

[7] J. Dai, X. Xu, J. Ke, J. Yin, Y. Dai, F. Yin, Y. Zhou, J. Li, Y. Fan, and K. Xu, "Self-oscillating triangular pulse generator based on 90° photonic-assisted phase shifter," *IEEE Photon. Technol. Lett.*, vol. 29, no. 3, pp. 271-274, 2017.

[8] J. Li, T. Ning, L. Pei, W. Peng, N. Jia, Q. Zhou, and X. Wen, "Photonic generation of triangular waveform signals by using a dual-parallel Mach-Zehnder modulator," *Opt. Lett.*, vol. 36, no. 19, pp. 3828-3830, 2011.

[9] Y. Gao, A. Wen, H. Zheng, D. Liang, and L. Lin, "Photonic microwave waveform generation based on phase modulation and tunable dispersion," *Opt. Exp.*, vol. 24, no. 12, pp. 12524-12533, 2016.

[10] X. Liu, W. Pan, X. Zou, D. Zheng, L. Yan, B. Luo, and B. Lu, "Photonic generator of triangular-shaped microwave pulses using SBS-based optical carrier processing," *J. Lightwave Technol.*, vol. 32, no. 20, pp. 3797-3802, 2014.

[11] W. H. Sun, W. Li, W. T. Wang, W. Y. Wang, J. G. Liu, and N. H. Zhu, "Triangular microwave waveform generation based on stimulated Brillouin scattering," *IEEE Photon. J.*, vol. 6, no. 6, 5501607, 2014.

[12] Y. Gao, A. Wen, W. Liu, H. Zheng, and S. Xiang, "Photonic generation of triangular pulses based on phase modulation and spectrum manipulation," *IEEE Photon. J.,* vol. 8, no. 1, pp. 7801609, 2016.

[13] W. Li, W. T. Wang, and N. H. Zhu, "Photonic generation of radio-frequency waveforms based on dual-parallel Mach-Zehnder modulator," *IEEE Photon. J.*, vol. 6, no. 3, 5500608, 2014.

[14] W. Li, W. T. Wang, W. H. Sun, W. Y. Wang, and N. H. Zhu, "Generation of triangular waveforms based on a microwave photonic filter with negative coefficient," *Opt. Exp.*, vol. 22, no. 12, pp. 14993-15001, 2014.

[15] F. Zhang, X. Ge, and S. Pan, "Triangular pulse generation using a dual-parallel Mach-Zehnder modulator driven by a single-frequency radio frequency signal," *Opt. Lett.*, vol. 38, no. 21, pp. 4491-4493, 2013.

[16] W. Chen, D. Zhu, Z. Chen, and S. Pan, "Full-duty triangular pulse generation based on a polarization-multiplexing dual-drive Mach-Zehnder modulator," *Opt. Exp.*, vol. 24, no. 25, 28606, 2016.

[17] EOSpace ultra-wideband modulators, http://www.eospace.com/

[18] Marki Microwave 90° modules, http://www.markimicrowave.com/hybrids/hybrids-products.aspx#90degree-Modules