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Research on photonic generation of quadrupling triangular-shaped waveform using external modulation

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ABSTRACT

We propose an improved approach to generate frequency-quadrupled triangular-shaped waveform signals based on two cascaded modulators. A dual-parallel Mach-Zehnder modulator (DP-MZM) is employed to provide the quadrupling RF modulation, after which two primary optical sidebands (± 2nd) are generated in spectrum. Then a dual-drive Mach-Zehnder modulator (DD-MZM) is followed to perform the optical double sideband (ODSB) modulation and signal with four sidebands (± 2nd and ± 6th) is obtained. By adjusting modulation index carefully, the power ratio of ± 2nd and ± 6th sidebands can be tuned to 9.5 dB. A piece of single mode fiber (SMF) is applied to remove the undesired harmonic. The expression of optical intensity is approximately equal to the Fourier expansion of ideal triangular-shaped waveform. The principle is illustrated by theory, simulation, and experiment. Finally, triangular-shaped waveform signals with repetition rate of 8 GHz, 12 GHz, 16 GHz and 20 GHz are generated.

Photonic arbitrary waveform generation has attracted much attention due to its important applications in all-optical data processing, communication system and radar system [1–4]. Triangular-shaped waveform, which is featured with linear raising-up and falling-down edges, has been widely used in all-optical signal processing and manipulation [5]. Typically, triangular-shaped waveforms can be generated through optical-spectrum-shaping method together with the frequency-to-time mapping (FTTM) technique [6]. In this method, the spectral envelope of an optical frequency comb is reformed by the spectral shaper to be a triangular-shaped version. Then the spectral envelope is mapped to temporal waveform in the photodetector after FTTM in a dispersion element. The drawback of this method is the usage of a mode-locked laser (MLL) which will lead to high cost and the generated triangular-shaped waveform signal usually have small duty cycle less than 1. In addition, triangular-shaped waveforms can be generated based on optoelectronic oscillator (OEO), which needs no external microwave source [7,8]. Nevertheless, the duty cycle of the triangular-shaped pulses generated by conventional OEO scheme is low and the repetition rate is difficult to tune. To solve these defects, waveform generation based on external modulation has been proposed [9–13]. In the external modulation system, a sinusoidal RF signal is firstly applied to a modulator to generate a series of sidebands. By controlling the phases and amplitudes of sidebands approximately equal to the Fourier expansion components of a triangular waveform, desired waveforms with full-duty-cycle are obtained. For example, in Ref. [9], we proposed a triangular-shaped waveform generation based on spectrum manipulation. To obtain triangular-shaped waveform signals, a single-drive Mach–Zehnder modulator (SD-MZM) is employed, after which five primary modulation sidebands are generated. By controlling the power of five modulation sidebands, optical intensity with expression corresponding to the first two-term Fourier expansion of triangular-shaped waveform signal can be obtained. In Ref. [10], a method to generate triangular-shaped waveform signal using a MZM incorporating stimulated Brillouin scattering (SBS) in an optical fiber is proposed. Triangular-shaped waveform can also be obtained by using time-domain synthesis [11], external modulation by cascaded MZMs [12] and MZM combined with an optical interleaver [13] or a dispersive element [14]. It can be seen from these approaches that external modulation is a feasible way to generate triangular-shaped waveform signals.

In this paper, we propose a photonic-assisted approach to generate frequency-quadrupled triangular-shaped waveform signals. Firstly, a DP-MZM is employed to implement the quadrupling RF modulation. By setting the modulation index of DP-MZM within a proper range, two primary optical sidebands (± 2nd) can be obtained in optical spectrum. Then the signal is transmitted to a DD-MZM for ODSB modulation, after which four sidebands (± 2nd and ± 6th) are achieved. Dispersion induced power fading in a piece of SMF is applied to remove

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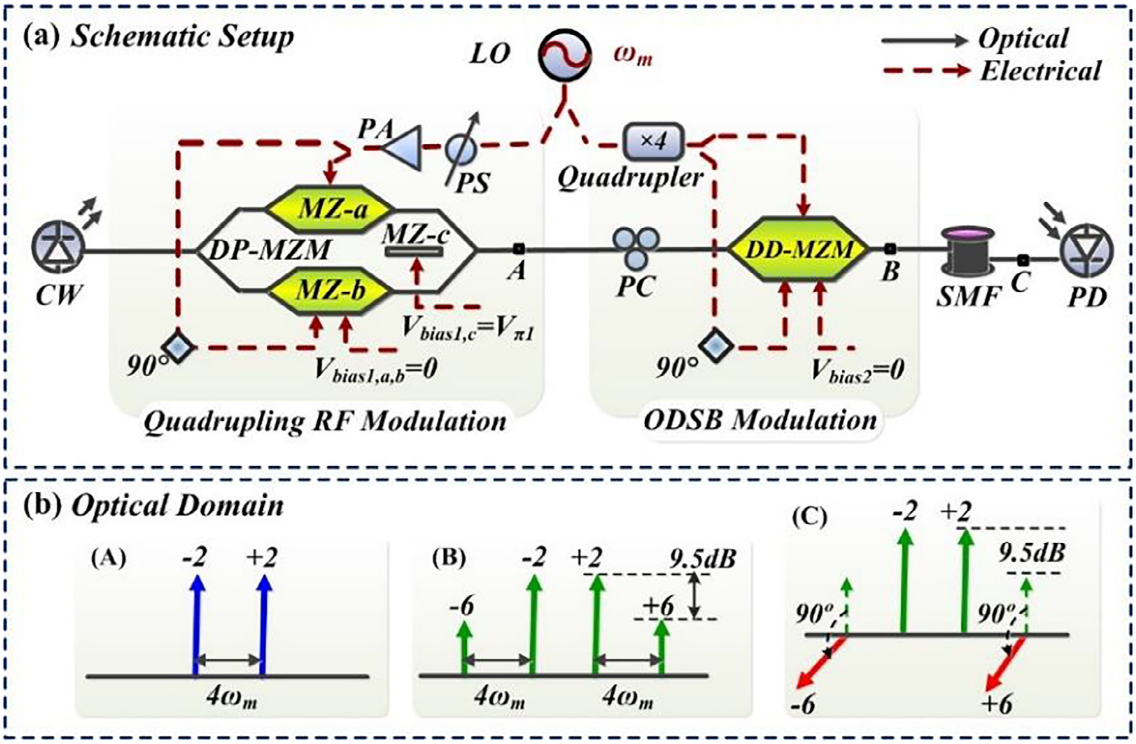

Fig. 1. (a) Schematic setup of the proposed triangular-shaped waveform signal generator. (b) The corresponding spectrum diagram. (CW, continuous-wave laser; LO, local oscillator; DP-MZM, dual-parallel Mach-Zehnder modulator; DD-MZM, dual-drive Mach-Zehnder modulator; PA, power amplifier; PS, phase shifter; PC, polarizer controller; SMF, single mode fiber; PD, photodiode.)

the undesired harmonic. Optical intensity expression corresponding to the first two-term Fourier expansion of a triangular-shaped waveform can be achieved. The quadrupling RF modulation and ODSB modulation are verified by a proof-of-concept experiment. Finally, a 16 GHz triangular-shaped waveform signal is generated by using a 4 GHz sinusoid signal.

1. Principle and theoretical analysis

The schematic diagram of the proposed triangular-shaped waveform generator is illustrated in Fig. 1. A light wave from a CW laser is firstly coupled into a DP-MZM, whose two sub-MZMs (MZ-a and MZ-b) are biased at maximum transmission point (MATP) and parent MZ-c is biased at minimum transmission point (MITP). A RF signal is split into two paths by a power divider. One path is divided into two parts by a 90° electrical bridge to drive two sub-MZMs, after which DP-MZM is under quadrupling RF modulation. The driving signal of DP-MZM is expressed as $V_{rf1}(t) = V_1 exp(j\omega_m t)$. The optical field of input light wave is $E_{in}(t) = E_0\exp(j\omega_0 t)$, in which E_0 and ω_0 denotes the amplitude and angular frequency. When the extinction ratio of DP-MZM is assumed to be infinite, the optical field at output of DP-MZM can be expressed as [15]

$$\begin{aligned}E_A(t) &= \frac{E_{in}(t)}{2}\left\{\begin{matrix}\exp[j\frac{V_1}{2V_{\pi1}}\cos(2\omega_m t)] + \exp[-j\frac{V_1}{2V_{\pi1}}\cos(2\omega_m t)] \\ -\exp[-j\frac{V_1}{2V_{\pi1}}\sin(2\omega_m t)]-\exp[j\frac{V_1}{2V_{\pi1}}\sin(2\omega_m t)]\end{matrix}\right\} \\ &= \frac{E_{in}(t)}{2}\sum_{i=-\infty}^{\infty} a_{4i-2}\exp[j(4k-2)\omega_m t]\end{aligned} \tag{1}$$

where $a_{4i-2} = [j^{4i-2} + j^{4i-2}(-1)^{4i-2}-(-1)^{4i-2}-1]J_{4i-2}(m_1)$. $J_n(\bullet)$ is the nth-order Bessel function of the first kind. The parameter $m_1 = \pi V_1/2V_{\pi 1}$ is the modulation index of DP-MZM, in which $V_{\pi 1}$ denotes the half-wave switching voltage of DP-MZM. Fig. 2 gives the relationship between m_1 and $J_{4i-2}(m_1)$. It can be seen that when m_1 is adjusted within a range from 1 to 3, the value of $J_6(m_1)$ and $J_{10}(m_1)$ are far smaller than that of $J_2(m_1)$. This indicates that the impact of harmonics higher than 2nd–order can be neglected.

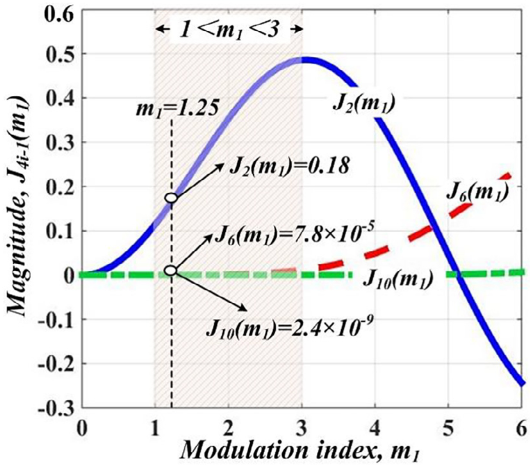

Fig. 2. Relationship between Bessel function of the first kind, $J_{4i-2}(m_1)$ and modulation index, m_1.

As a modulator with relatively small modulation index is preferred, we tune m_1 to 1.25 for the following analysis. In this case, $J_6(m_1)$ and $J_{10}(m_1)$ are 7.8×10^{-5} and 2.48×10^{-9}, while $J_2(m_1)$ is 0.18. This indicates that the impact of the 6th- and 10th-order harmonics is negligibly small and only the ± 2nd-order harmonics are considered. Thus, the optical field at the output of DP-MZM (point A) can be simplified as

$$E_A(t) \propto J_{-2}(m_1)\exp(-j2\omega_m t) + J_{+2}(m_1)\exp(j2\omega_m t) \tag{2}$$

It is obvious that after quadrupling RF modulation, signal with only ± 2nd-order sidebands and a frequency spacing of $4\omega_m$ are kept in optical spectrum as shown in Fig. 1(A). Then the modulated signal is coupled into a DD-MZM to provide the ODSB modulation. In Fig. 1,