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Multiple microwave waveform generation by a dual-loop optoelectronic oscillator

Chuang Ma [a], Jinlong Yu [a], Wenrui Wang [a], Ju Wang [a,*], Yang Yu [a], Tianyuan Xie [a], Enze Yang [a], Yang Jiang [b]

[a] School of Electrical and Information Engineering, Tianjin University, No. 92 Weijin Road, Tianjin 300072, China
[b] School of Physics, Guizhou University, Guiyang, 550025, China

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ABSTRACT

A self-starting multiple microwave waveform signal generator based on a dual-loop optoelectronic oscillator (OEO) is proposed. The structure of the dual-loop OEO with two wavelengths can suppress the random beating noise effectively and generate the microwave signal with low phase noise (−119.8 dBc/Hz at 10 kHz). Then square waveform is generated by setting the modulation index to be 1.15. Sawtooth (Reversed-sawtooth) waveform is obtained by combining a square and a frequency doubling sinusoidal signal which is got by setting the bias of the other MZM driven by OEO at the null point (maximum point). The triangular waveform is obtained by combining two oscillation signal envelopes with a relative 1/4 period time delay, when the modulation index of the MZM is set to 0.7555. The operation principle is theoretically analyzed and simulated. In experimental demonstration, full-duty-cycle and high quality square, sawtooth (reversed-sawtooth) and triangular waveform signals with low phase noise at 4.9641-GHz are achieved. An external synthesizer is replaced by the high-quality microwave signal in this structure.

1. Introduction

Arbitrary microwave waveforms has attracted great attentions in recent years because of its widespread applications in wireless communication, all-optical microwave signal processing, instrumentation systems and radar [1–4]. Traditionally, arbitrary microwave waveforms (AWG) are generated by electronic methods but the frequencies of the generated signals are limited by the bandwidth of all electronic devices. Due to the high cost of the high-frequency electronic devices traditional large-bandwidth AWG are very expensive. In comparison, high-frequency optoelectronic devices have lower costs. Therefore, the AWG based on microwave optoelectronic technology has the potential to reduce the cost of the large-bandwidth AWG. In addition, with the development of microwave photonic technology (MPT), many practical high-frequency systems tend to directly process optical signals rather than electrical signals [2–4]. Therefore, the application of the AWG based on MPT in this area can eliminate the need for photoelectric conversion, and can even be embedded directly in the system. Moreover, electronic techniques also have other shortcomings, e.g., large loss, vulnerability to electromagnetic interference, and so on. With the development of photonic technology in recent decades, these defects in electronic technology could be effectively overcome.

Therefore, lots of new approaches which take advantage of photonic technology to generate arbitrary microwave waveforms have been reported in recent years. One popular way is Fourier synthesis method. [5]. This method shows good performance in generation of arbitrary microwave waveforms, while the insertion loss, complexity in the setup and alignment control are still great challenges for further optimization. Another method for arbitrary waveform generation is the combination of optical-spectrum-shaping method and the frequency-to-time mapping (FTTM) technique [6,7]. In this approach, the optical frequency comb is tailored by the spectral shaper to be a scaled version of the desired waveform. Then the tailored optical frequency comb is mapped to the temporal waveform by using FTTM. This method may cause relatively low flexibility for different waveforms generation due to the use of cascaded optical filters. In addition, among these approaches, a mode-locked laser (MLL) is used as the optical comb source, which leads to high cost and the generated waveforms usually have small duty cycle.

External modulation of a continuous wave (CW) light provides a solution to generate arbitrary waveforms with full-duty-cycle. A series of optical sidebands are generated due to the nonlinearity of the external modulator. The desired waveforms are generated by manipulating the

* Corresponding author.
E-mail address: tdwangju@126.com (J. Wang).

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phases and amplitudes of these modulation harmonics. Many methods are proposed to carry out this process. In [8,9], full-duty-cycle triangular and sawtooth waveforms are generated by using a dual electrode Mach–Zehnder modulator (De-MZM) and a length of dispersion fiber. The fiber in the system is used to suppress the unwanted harmonics. However, the frequency of the generated waveform cannot be changed for a given length of dispersive fiber. To generate frequency tunable arbitrary waveforms, an architecture using a polarization modulator (PolM) in a Sagnac loop was proposed [10]. Due to the different modulation efficiency for the clockwise and counter-clockwise light waves in the Sagnac loop, the power of modulation sidebands can be controlled identical to fit the Fourier series expansion of the desired waveforms. Although this method shows successful tunable frequency arbitrary waveforms generation, the system may suffer from stability problem due to the use of Sagnac interferometer. In paper [11], a dual-parallel Mach–Zehnder modulator (DPMZM) also be employed for generation of arbitrary waveforms. In this approach, the biases of the two sub-MZMs and the parent MZM of the DPMZM should be accurately and simultaneously controlled to generate the required harmonics. In addition, dispersion devices or optical bandpass filter has to be employed to satisfy the phase condition. Triangular waveform can also be generated by a signal-drive MZM [12–15]. According to the schemes, additional devices (such an optical interleaver(OI), a microwave photonic filter (MPF) [13], stimulated Brillouin scattering (SBS) [14], or polarization-dependent modulation efficiency [15]) have to be used to select out the first- and the third-order harmonics among the modulation sidebands. These schemes indicate a good performance of triangular waveform generation. However, they have the limitation on generating other waveforms.

Besides the approaches mentioned above, arbitrary microwave waveforms generation based on time-domain processing have been proposed in [16,17]. In [16], the desired waveform is synthesized by the superposition of signals, and the high-order frequency components are obtained under the injection-locking process in a DFB-LD. In [17], two single-drive Mach–Zehnder modulators biased at quadrature point are severed as optical pulse carvers. The desired microwave waveform signals are generated by carving and overlapping optical field envelopes. Although these approaches avoid the complex manipulation of spectral lines, the time delay of the signal envelopes should be accurately controlled.

In summary, an external microwave source is always required to drive a modulator for the generation of arbitrary microwave waveforms [5–17]. Hence the quality of the generated waveforms is determined by the phase noise of the external microwave signals. Considering that an optoelectronic oscillator (OEO) can generate high-quality microwave signals, triangular waveform generators based on OEOs were reported [18–20]. In these works, microwave sources are replaced by single-loop OEOs, and triangular waveforms with low phase noise are generated successfully. However, only the triangular waveforms have been generated in these works.

In this paper, a novel multiple waveform signal generator based on a dual-loop OEO is proposed and demonstrated. When the oscillation is established, a 4.9641-GHz microwave signal with the low phase noise of −119.8 dBc/Hz @10 kHz is generated by OEO, and the corresponding timing jitter is around 161-fs. In this process, the microwave signal is modulated onto a MZM (MZM1). When the modulation index of the MZM1 is set to be 1.15, high quality square waveform can be generated. Sawtooth (Reversed-sawtooth) waveform with low phase noise can be obtained by combining a square waveform and a frequency doubling sinusoidal signal. The frequency doubling signal can be obtained by setting the bias point of the other MZM (MZM2) which is driven by OEO at the null point (maximum point). When the modulation index of the MZM1 is set to be 0.7555, the triangular waveform with low timing jitter can be generated by a superposition of two oscillation signal envelopes with a relative 1/4 period time delay. In this work, the operation principle is theoretically analyzed and simulated. In addition, the external microwave reference source is not required in this system.

2. Principle

2.1. Dual-Loop optoelectronic oscillator with two wavelengths

The fundamental frequency signal of the photonic microwave waveform generation is obtained by a dual-loop optoelectronic oscillator with two wavelengths. As shown in Fig. 1, optical carriers with two wavelengths are emitted from two DFB lasers, combined using a wavelength division multiplexer (WDM1), and then fed into a MZM (MZM1). Two polarization controllers (PC1 and PC2) are used to align the polarization states of the optical carriers to achieve the maximum efficiency of the modulation in MZM1. The optical beam is then split into two branches by WDM2. The optical signals with each wavelength go through two spans of single mode fiber (SMF) respectively and then combined by WDM3. Then the combined optical carrier is converted into microwave signal by the photodetector (PD). After passing through a bandpass filter (BPF), a microwave amplifier (MA) and a microwave tunable attenuator (TA1) successively, the microwave signal is finally fed back to the microwave port of the MZM1 to constitute the feedback loops. The MA is adopted to ensure sufficient loop gain to guarantee the oscillation. The TA1 is necessary for the microwave waveforms generation later, but not for OEO oscillating.

The dual-loop OEO is analyzed theoretically in [21,22]. In short, single mode and high-quality fundamental microwave frequency signal is generated by employing fiber with different lengths in each loop. SMF1 is long to ensure a narrow bandwidth, i.e., high Q factor. This provides a guarantee for the production of high quality arbitrary microwave waveforms. SMF2 is short to ensure large mode spacing. Thus single mode oscillating inside the bandwidth of the BPF filter can be established. Besides, the frequency difference of the optical carriers in two loops is much larger than the bandwidth of the PD. Therefore, the random interference and beating noise cannot be introduced.

2.2. Microwave waveforms generation

Note that only the fundamental frequency signal can pass the BPF, thus the electronic signal fed back to the microwave port of the MZM1 is a sinusoidal signal no matter what waveform is in the optical domain. The sinusoidal signal can be expressed as $V(t) = V_m cos\,(\omega_m\, t)$, where V_m is the amplitude and ω_m is the angular frequency of the signal generated by OEO. Assuming the angular frequency of the optical carrier is ω_0, the optical field at the output of the MZM1 can be approximately expressed by:

$$E_{out}(t) = E_0 \cos\left[\frac{\varphi}{2} + \frac{\pi V(t)}{2V_\pi}\right] \cos\left(\omega_0 t\right) \tag{1}$$

where E_0 is the optical field amplitude, $\varphi = \pi\, V_{bias}/V\pi$ is the phase shift determined by the DC-bias voltage V_{bias}, and V_π is the half-wave voltage of the modulator.

If the output signal is detected by a PD directly, the photo-current (the signal at point (i) and (ii)) can be expressed as:

$$\begin{aligned} i(t) &= \frac{RE_0^2}{2}\left[1 - \cos\left(\varphi + \frac{\pi V(t)}{V_\pi}\right)\right] \\ &= \frac{RE_0^2}{2}\left\{1 - \cos\left[\varphi + 2\beta\cos\left(\omega_m t\right)\right]\right\} \end{aligned} \tag{2}$$

where R is the responsivity of the PD and β is the modulation index of the MZM, defined as $\beta = \pi\ V_m/2V_\pi$. Then the MZM1 is biased at quadrature point ($\varphi = \pi/2$), applying Jacobi–Anger expansion, Eq. (2) can be rewritten as:

$$\begin{aligned} i_{1,2}(t) &= \frac{RE_{1,2}^2}{2}\left[1 - \cos\left(\frac{\pi}{2} + 2\beta\cos\left(\omega_m t\right)\right)\right] \\ &= \frac{RE_{1,2}^2}{2}\left[1 - 2\sum_{n=1}^{\infty}(-1)^n J_{2n-1}(2\beta)\cos\left[(2n-1)\,\omega_m t\right]\right] \end{aligned} \tag{3}$$

where J_n is the first kind of Bessel function with order n.