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Photonic generation of microwave waveforms based on a dual-loop optoelectronic oscillator

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ABSTRACT

A novel photonic scheme of microwave waveforms generator based on a dual-loop optoelectronic oscillator (OEO) is experimentally verified. A 10-GHz microwave signal generated by OEO is modulated onto the directly modulated laser (DML) and the phase modulator (PM) simultaneously. By adjusting the driven power of the DML and the PM and the phase difference between the pulse signal inputted into the PM and the PM's driven signal, the desired optical spectrum is obtained. By passing appropriate dispersion, the optical spectrum can be converted into desired waveform. In this experiment, a series of waveforms with the shapes of sawtooth/reversed-sawtooth, triangle, and pulse are generated.

1. Introduction

Generation of microwave waveform has been highly expected for applications in the fields of wireless communication, all-optical microwave signal processing, instrumentation systems and radars [1–4]. Traditionally, arbitrary microwave waveforms are generated by electronic methods but the frequencies of the generated signals are limited by the bandwidth of electronic devices. Compared with the electronic ones, photonic approaches exhibit more advantages, such as wide bandwidth, low loss and immunity to electromagnetic interference [5].

Nowadays, many photonic approaches for microwave waveform generation have been proposed. One popular way is to modulate a continuous wave (CW) externally, in which the third order approximation of microwave waveforms are generated by manipulating the phases and amplitudes of the modulation harmonics. Several demonstrations have carried out this process, such as dual-parallel Mach–Zehnder modulator (DP-MZM) [6–8] combined with dispersion elements or tunable optical band-pass filter (TOBF), polarization modulator (PolM) inserted in a Sagnac Loop [9], single-drive MZM based on optical interleaver (OI) [10], polarization-dependent modulation [11], microwave photonic filter (MPF) [12], two cascaded single-drive Mach–Zehnder modulators [13,14], or stimulated Brillouin scattering (SBS) [15]. Waveform generation by using time-domain synthesis [16,17] is another approach, in which the optical are modulated by a MZM with a sinusoidal driving signal and the desired triangular waveform can be obtained by the superposition of signal envelopes with frequency multiplexing and proper time delay [16], or directly overlapping two modulated signal envelopes [17]. Photonic generation of arbitrary waveforms can also be implemented through frequency-to-time mapping (FTTM) technique, such as triangle-shaped, rectangle-shaped and arbitrary-shaped pulses generator [18–21]. This approach shows good performance and ability in generating high order approximation of microwave waveforms.

Summing up the schemes above, all of them are required an external microwave source to drive the modulator for generation of waveforms. 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 [22], triangular waveform generators based on OEOs were reported [23,24]. In these works, the single-loop OEOs are used as the microwave divers, however, they are independent from the triangular waveform generation module, and only the triangular waveforms can be generated. Meanwhile, many other OEOs have been proposed in recent years, which might provide lots of possibilities for low-timing-jitter waveforms generation.

In this paper, a novel multiple microwave waveform signal generator based on a dual-loop OEO is proposed and experimentally demonstrated. When the oscillation is established, a 10-GHz microwave signal with the phase noise of −115.3 dBc/Hz @10 kHz is generated by OEO. Then the 10-GHz signal is modulated onto the directly modulated laser (DML) and the phase modulator (PM) simultaneously, to generate an optical frequency comb (OFC). A tunable optical delay line (ODL) in-between is employed to shape the generated OFC. By utilizing the signal

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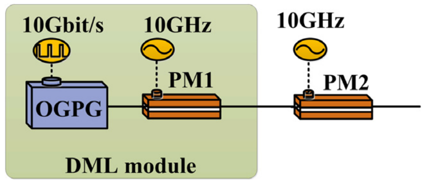

Fig. 1. Simulation diagrams of optical frequency combs generation. OGPG: optical Gaussian pulse generator, PM: phase modulator.

mode fiber (SMF) with appropriate length, the generated OFC can be converted into desired waveform. In this work, a sawtooth (or reversed-sawtooth) waveform, a triangular waveform and a pulse with 10-GHz are experimentally generated. The external microwave source used in the conventional photonic waveform signals generation methods [6–21] is replaced by the self-oscillating high-quality microwave signal generated by the OEO. In addition, the PM in this system not only plays a role in establishing the dual-loop OEO to suppress the side mode but also plays a role in shaping the OFC.

2. Principle

The optical pulse of the DML driven by a sinusoidal signal can be expressed as [25]

$$E(t) = E_0 \exp[-\frac{t^2}{2T_0^2}]\exp[-j(\omega_0 t + \theta_1 \cos 2\pi f_m t)] \quad (1)$$

where E_0 is the amplitude of optical field, ω_0 is the angular frequency, f_m is modulation frequency, θ_1 is the equivalent phase modulation index of DML and T_0 is the full width at half maximum (FWHM) of the pulse.

When the pulse emitted from the DML is modulated by a PM driven by the sinusoidal signal with a frequency of f_m, the modulated electrical field can be expressed as

$$E(t) = E_0 \exp(-\frac{t^2}{2T_0^2})\exp[-j(\omega_0 t + \theta_1 \cos 2\pi f_m t + \theta_2 \cos(2\pi f_m t + \Delta\varphi))] \quad (2)$$

where, θ_2 is the modulation index of the PM, and $\Delta\varphi$ is the phase difference between the signal inputted into PM and the PM's driven signal. The optical frequency of the pulse can be expressed by applying Jacobi Anger expansion to Eq. (2).

$$E = \sum_{n=-\infty}^{+\infty} T_0 \exp[-\frac{T_0^2(nf_m)^2}{2}] \otimes \sum_{n=-\infty}^{+\infty} (-j)^n J_n(\theta_1) \otimes \sum_{n=-\infty}^{+\infty} (-j)^n J_n(\theta_2)\exp(jn(\Delta\varphi)) \quad (3)$$

where J_n is the Bessel function of the first kind of order n. The optical frequency chirp of the pulse can be described as

$$\frac{\partial V}{\partial t} = -\frac{1}{2\pi}\frac{\partial^2 \Phi}{\partial t^2} = -2\pi f_m^2[\theta_1 \cos(2\pi f_m t) + \theta_2 \cos(2\pi f_m t + \Delta\phi)] \quad (4)$$

where ϕ is the phase of the pulse.

Obviously, this method is able to generate many comb lines with the frequency spacing of f_m. The shape of the OFC can be adjusted by changing θ_1, θ_2 and $\Delta\varphi$. This process can be simulated by OptiSystem.

The schematic of the simulation is illustrated in Fig. 1. A DML module is composed of an optical Gaussian pulse generator (OGPG) and a PM (PM1), which are driven by a 10-Gbit/s bit sequence and a 10-GHz sinusoidal signal respectively, in order to generate pulses. Then the generated pulses from the DML module are launched into the other PM (PM2) which is also driven by a 10-GHz sinusoidal signal. In the simulation the amplitudes of driven signals of PM1 and PM2 are proportional to θ_1 and θ_2, respectively. The value of $\Delta\varphi$ can be changed by changing the phase difference between the pulse signal inputted into PM2 and the PM2's driven signal. For generating a Gaussian pulse expressed by Eq. (1), the wavelength and width of the OGPG and the amplitude of the driven signal of PM1 are set as 1551 nm, 0.2bit and 1.5 a.u. respectively. The waveform and the corresponding OFC of the generated pulse are shown in Fig. 2(a) and (b). It can be seen from Fig. 2(a) and (b) that the repetition rate of the pulse and the interval of the adjacent harmonic components are 10 GHz and 0.08 nm respectively.

Then the shape of the OFC can be adjusted by changing the amplitude of the PM2's driven signal and the phase difference between the pulse signal inputted into PM2 and the PM2's driven signal. When they are set as 2.7 a.u. and 0.25π, the OFC and corresponding waveform are shown in Fig. 2(c) and (d). Comparing Fig. 2(c) with Fig. 2(b) we can find that the OFC is shaped from Gauss shape to sawtooth shape. On the other hand, we can find that the waveform in Fig. 2(d) is still a 10-GHz Gaussian pulse by comparing it with Fig. 2(a). By passing about 57ps/nm dispersion (provided by about 3 km SMF which D = 19 ps/(nm × km) in OptiSystem), a sawtooth waveform can be obtained, as seen in Fig. 3(a).

Keeping the powers of driven signals of PM1 and PM2 unchanged and adjusting the phase difference between the pulse signal inputted into PM2 and the PM2's driven signal to 0.75π and 1.5π, the OFC can be shaped to reversed-sawtooth shape and triangular shape as shown in Fig. 3(b) and (d). The reversed-sawtooth waveform and triangular waveform can also be obtained after 57ps/nm and 87.4ps/nm dispersion in Fig. 3(c) and (e).

3. Experiments

An experiment is performed based on the setup shown in Fig. 4 to verify the feasibility of the proposed scheme. A beam of CW light at 1550.08 nm is emitted by DML. After passing through SMF1, an ODL and a polarization controller (PC), the CW light is injected into a PM followed by an erbium-doped fiber amplifier (EDFA). The PC is used to align the polarization state of the input light with the axis of the PM. The EDFA is used for compensating the insertion loss in the system. Then the optical beam is divided into two parts by a 90% : 10% optical coupler (OC). One part (10%) acts as the optical signal output for generating microwave waveform, and the other part (90%) is converted into a microwave signal by a PD after passing through SMF2. Then the microwave signal is filtered by a band-pass filter (BPF) with the central frequency of 10 GHz and bandwidth of 10 MHz. After the BPF and an radio frequency (RF) amplifier (AM), the microwave signal is divided into two branches by an 3 dB electric coupler (EC). Then the two branches are fed back to the DML and the PM after passing through two tunable attenuators (TAs) respectively, completing the dual loops. In this scheme, the PM EDFA OC SMF2 (850 m) PD BPF AM AC and TA1 are formed a short cavity to ensure large mode spacing. The DML SMF1 (2000 m) ODL PC PM EDFA OC SMF2 (850 m) PD BPF AM AC and TA2 are formed a long cavity to ensure a narrow bandwidth, i.e., high Q factor [26]. This provides a guarantee for the production of high quality microwave waveforms.

A 10-GHz microwave signal with low phase noise is achieved by the dual-loop OEO. It turns to be a completely single-loop OEO when the PM is taken off. The electrical spectrum measured by the spectrum analyzer (Agilent 8564EC) under this condition is shown in Fig. 5(a) by dotted line. It can be shown that the measured side mode suppression ratio (SMSR) is 32 dB and mode spacing is about 70.4 kHz, which corresponds to the 2850 m cavity. When the PM is inserted back, dual-loop OEO is established again. The measured electrical spectrum and phase noise are shown in Fig. 5(a) and (b) by solid line. It can be seen in Fig. 5(a) that the (SMSR) is improved from 32 dB to 60 dB. The phase noise of the generated microwave signal of the dual-loop OEO is −115.3 dBc/Hz at 10 kHz offset frequency as shown in Fig. 5(b). The corresponding root-mean-square (RMS) timing jitters of the signal is about 139.5 fs, calculated by integrating the noise power spectrum density measured above using the following equation [27]:

$$\sigma = \sqrt{2\int_{f_{\min}}^{f_{\max}} L(f)df}/2\pi f_{osc}$$