Time Duration Tunable Fourier Domain Mode-Locked Optoelectronic Oscillator Based on a Frequency Shifting Loop

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***Abstract*—A time-duration tunable Fourier-domain mode-locked optoelectronic oscillator (FDML-OEO) based on a frequency-shifting loop (FSL) is proposed and experimentally demonstrated. Experimental results show that a linear frequency modulation (LFM) waveform with a tunable time duration is generated.**

***Keywords*—optoelectronic oscillator, Fourier domain mode-locking, frequency shifting loop, time duration tunable, microwave generation.**

I. INTRODUCTION

Broadband microwave waveforms play an important role in modern wireless communication, radar reconnaissance and radar imaging systems. Purely electronic circuit such as a voltage-controlled oscillator (VCO) is usually the most common method to generate broadband microwave waveform [1]. However, the frequency and bandwidth of a microwave waveform generated by an electronic system are limited. On the other hand, photonic-assisted techniques have been proposed to generate and process microwave signals or waveforms at much higher frequency and broader bandwidth in the optical domain [2, 3]. Various photonic-assisted approaches have been demonstrated such as space-to-time mapping and temporal pulse shaping [4-6]. Recently, the concept of Fourier domain mode locking originally proposed for broadband optical waveform generation has been introduced to the microwave photonics (MWP) domain for broadband linear frequency modulation (LFM) waveform generation using an optoelectronic oscillator (OEO) [7]. By using a frequency-sweeping microwave photonics filter (MPF) in an OEO, an LFM waveform can be generated as long as the sweeping rate of the MPF is equal to or an integer times of the OEO loop free spectral range (FSR). Generally, the time duration of an LFM waveform generated by a Fourier domain mode-locked OEO (FDML-OEO) is determined by the round-trip time delay of the OEO loop. Although a few techniques such as harmonic mode-locking can be used to generate an LFM waveform with a different waveform duration [8], the largest waveform duration is still constrained by the OEO loop length.

In this paper, we propose and experimentally demonstrate a time-duration tunable FDML-OEO based on a frequency shifting loop (FSL). The bandwidth and time duration of the generated LFM waveform is tuned by changing an external driving signal applied to a laser source. The results show that the time duration of the LFM waveform can be tuned from 8.1 to 13.53 μs with a tuning step of 1.81 μs by controlling the recirculation light in the FSL for 0, 1, 2, and 3 times. An LFM waveform with a longer duration can be generated if the recirculation light is traveling in the FSL for more round times.

II. PRINCIPLE

Fig. 1 shows the schematic diagram of the proposed time-duration tunable FDML-OEO. A continuous-wave (CW) light from a laser diode (LD) modulated by an electrical triangular waveform is applied to a phase modulator (PM). The optical signal at the output of the PM is then sent into an FSL through a polarization controller (PC1). The FSL is the critical part of the proposed OEO, which consists of a dual-parallel Mach-Zehnder modulator (DPMZM), a PC (PC2), a spool of single mode fiber (SMF1), an erbium-doped fiber amplifier (EDFA1), a tunable optical fiber (TOF1), and a 2×2 optical coupler. An external microwave signal is applied to the DPMZM through a 90° electrical hybrid. The two sub-MZMs of the DPMZM are biased at the minimum transmission point, while the main MZM is biased at the quadrature point, so as to perform a carrier-suppressed single sideband (CS-SSB) modulation. When the light circulates in the FSL, its frequency is shifted. Thus, an optical frequency comb (OFC) is generated at the output of the FSL. PC1 and PC2 are used to reduce the polarization dependent loss in the FSL. EDFA1 provides a gain to compensate for the loss in the loop. TOF1 is used to control the spectral width of the comb and reduce the influence of the amplified spontaneous emission (ASE) noise from EDFA1. Each comb line has a specific time delay, a second TOF (TOF2) is used to select one line that has the desired time delay. After passing through an SMF (SMF2) and being amplified by another EDFA (EDFA2), the optical signal is reflected by a phase-shifted fiber Bragg grating (PS-FBG) through an optical circulator (OC). Then, the optical signal is detected at a photodetector (PD). The electrical signal is amplified by an electrical amplifier (EA) and fed back to the PM to form an oscillation loop.

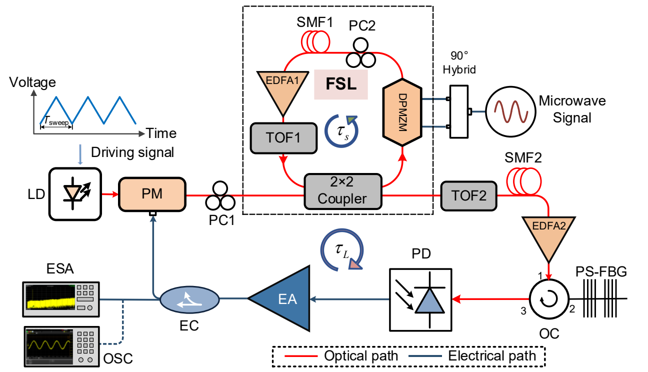

Fig. 1. Schematic diagram of the proposed time-duration tunable FDML-OEO based on an FSL. LD: laser diode, PC: polarization controller, PM: phase modulator, DPMZM: dual-parallel Mach-Zehnder modulator, TOF: tunable optical filter, SMF: single mode fiber, EDFA: erbium-doped fiber amplifier, OC: optical circulator, PS-FBG: phase-shift fiber Bragg grating, PD: photodetector, EA: electrical amplifier, ESA: electrical spectrum analyzer, and OSC: oscilloscope.

Thanks to the narrow transmission window within the reflection band of the PS-FBG, phase-modulation to intensity-modulation (PM-IM) conversion is realized and a microwave photonics filter (MPF) is implemented. The central frequency of the passband of the MPF is determined by the frequency difference between the LD and the PS-FBG notch. Thus, frequency sweeping of the MPF can be achieved by sweeping the wavelength of the LD, which is done by driving the LD with a triangular current.

To realize Fourier domain mode-locking, the frequency sweeping period of the LD (T_{sweep}) should be synchronized with the time delay of the OEO loop. Assuming that the round-trip delay of the FSL is τ_s, and the time delay of the rest part of the OEO loop is τ_L, the FDML in the proposed OEO can be realized when T_{sweep} is synchronized with the time delay of the selected n-th optical comb line, which is given by

$$T_{sweep} = \tau_L + n\tau_s \tag{1}$$

where, n = 0, 1, 2, … N (N is a positive integer) is the recirculation number. Note that since the notch of the PS-FBG is fixed, the frequency of the LD should be tuned to ensure that the n-th comb line can be reflected by the PS-FBG. The frequency of the n-th comb line of the OFC is given by $f_n=f_0-nf_s$, where f_0 and f_s are the frequencies of the LD and the sinusoidal microwave signal applied to the DPMZM, respectively. Then, the frequency of the LD f_0 should be equal to $f_{notch}-f_{osc}+nf_s$, where f_{osc} is the instantaneous oscillation frequency of the OEO, and f_{notch} is the frequency of the PS-FBG notch.

III. Results and Discussions

An experiment based on the setup in Fig. 1 is carried out to verify the effectiveness of the proposed OEO. The LD that is modulated by a triangular waveform from a waveform generator (WG) has an output power of 16 dBm. The microwave signal applied to the DPMZM is a sinusoidal signal of 17 GHz. The notch wavelength and the 3-dB bandwidth of the PS-FBG are 1549.88 nm and 350 MHz, respectively. The lengths of SMF1 and SMF2 are 330 m and 1660 m, respectively. The EA provides a gain of 22 dB. The optical and electrical spectra are measured by an optical spectrum analyzer (OSA) and an electrical spectrum analyzer (ESA), respectively. The temporal waveform is acquired by an oscilloscope (OSC) with a sampling rate of 80 GSa/s.

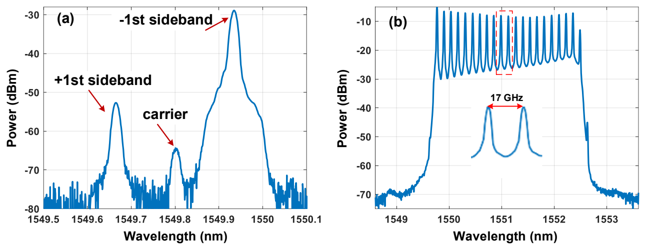

Fig. 2. (a) Optical spectrum of the CS-SSB modulation. (b) Optical spectrum at the output of the FSL, and the inset shows the zoomed-in view of two adjacent frequency lines.

Fig. 2(a) shows the result of the CS-SSB modulation. As can be seen, an optical sideband (-1st order sideband) is generated and the other sideband (+1st order sideband) and the optical carrier are supressed. Although residual carrier and +1st order sideband can be found, they are much lower than the -1st order sideband, which has little impact on the performance of the oscillation. Fig. 2(b) shows the spectrum of the OFC observed at the output of the 2×2 optical coupler. As can be seen, the optical power difference of the whole comb teeth is less than 3 dB. It should be noted that the signal-to-noise ratio (SNR) of the generated optical comb decreases as the recirculation number increases, which is mainly attributed to the accumulation of the ASE noise in the FSL. Better results can be expected if an EDFA with a lower noise figure and a higher saturation output power is used.

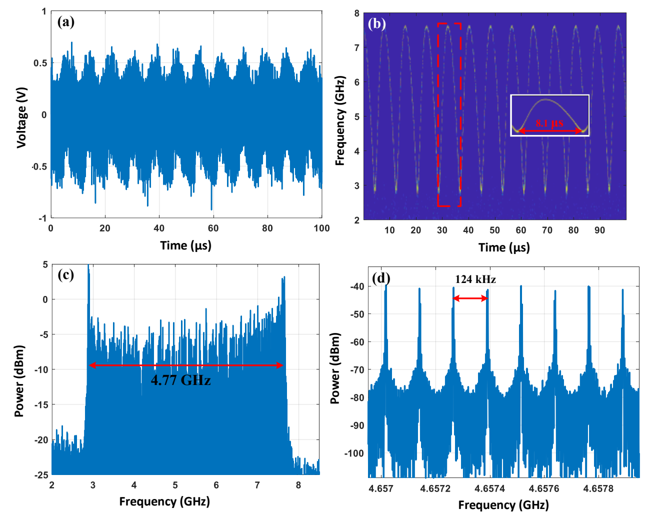

Fig. 3. Generated LFM waveform. (a) Temporal waveform. (b) Instantaneous frequency distribution. The inset shows a zoom-in view. (c) The spectrum of the waveform. (d) The spectrum with a span of 1 MHz.

In order to evaluate the performance of the FDML-OEO, the FSL is closed and the passband of TOF2 is set nearby the notch of the PS-FBG. First, the condition of n=0 is tested by letting the carrier from the LD pass through TOF2 directly. Although the light still can recirculate in the FSL, the frequency shifted light will be blocked by TOF2. The sweeping period of the LD is synchronized with the whole round-trip time of the OEO loop apart from the FSL (τ_L). Fig. 3(a) shows the temporal waveform of the generated LFM waveform with a whole sampling time of 100 μs. The instantaneous frequency distribution of the temporal waveform is calculated by performing a short-time Fourier transform, as shown in Fig. 3(b). A zoom-in view in Fig. 3(b) shows that the period of the generated LFM waveform is about 8.1 μs, which is equal to the loop delay (τ_L) of 8.1 μs. Fig. 3(c) shows the generated LFM waveform with a bandwidth of 4.77 GHz. Fig. 3(d) displays the oscillating modes with a span of 1 MHz. The oscillation mode interval is 124 kHz, which is equal to the reciprocal of the loop time delay.

By changing the peak-to-peak voltage of the triangular waveform, the bandwidth of the generated LFM waveform can be tuned. Fig. 4 shows the generated LFM waveforms with different bandwidths when the recirculation number is three, which are obtained by changing the peak-to-peak voltage of the triangular waveform from 30 to 140 mV. As can be seen, the bandwidth can be changed in a wide frequency range. The achievable bandwidth is limited by the reflection bandwidth of the PS-FBG.

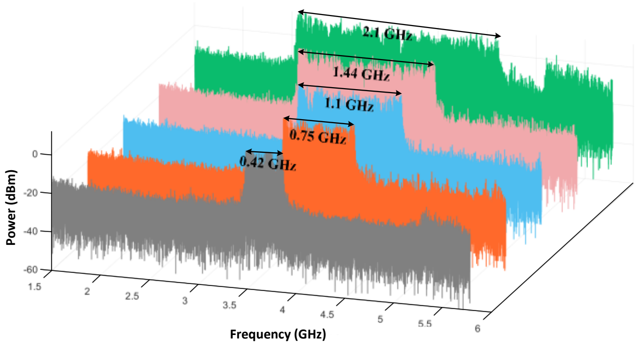

Fig. 4. LFM waveforms generated by the proposed OEO with different bandwidths.

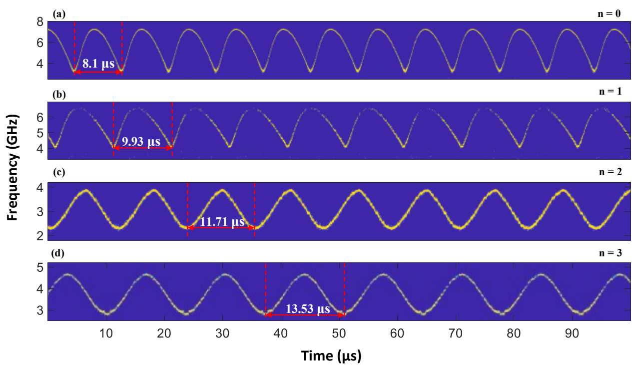

Fig. 5. Instantaneous frequency distributions of the generated LFM waveforms with different time durations. The instantaneous frequency distributions when the circulation numbers are (a) zero, (b) one, (c) two, and (d) three.

To verify that the proposed system can realize LFM waveform generation with a tunable time duration, we change the frequency sweeping period of the LD to let the carrier, 1st, 2nd, and 3rd comb lines pass through TOF2. The temporal waveforms are sampled and the instantaneous frequency distributions are calculated, as shown in Fig. 5. When the carrier is filtered out by TOF2, an LFM waveform with a time duration of 8.1 μs is generated, and every round-trip, the time duration is increased by 1.81 μs, which is equal to the time delay of the FSL. A time duration of 13.53 μs is realized in the experiment when the recirculation number is three. Moreover, since more than ten frequency lines is obtained by the FSL, the recirculation number can be further increased. Unlike a traditional FDML-OEO, the proposed system can break the limitation of the physical loop length and generate time duration increased LFM waveforms.

IV. Conclusions

An FDML-OEO for LFM waveform generation with an adjustable time duration was proposed and experimentally demonstrated. The key contribution of the work is the introduction of an FSL in the FDML-OEO, by which an optical comb with different comb lines having different time delays is generated. By choosing one comb line that has a specific time delay, the OEO with the desired loop time delay could be implemented which was used to generate an LFM waveform with the desired time duration. The proposed FDML-OEO for LFM waveform generation may find various applications in modern communication and radar systems.

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