Tunable Optical Frequency Comb Generation Based on an Optoelectronic Oscillator

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***Abstract*— A novel approach to the generation of an optical frequency comb with a widely tunable center wavelength and comb spacing based on an optoelectronic oscillator (OEO) is proposed and experimentally demonstrated. The OEO is implemented using a polarization modulator (PolM), a phase-shifted fiber Bragg grating (PS-FBG), and a photodetector (PD). The PolM is a special phase modulator that supports phase modulation along the two principal axes with opposite modulation indexes. The joint operation of the PolM, the PS-FBG, and the PD corresponds to a frequency-tunable microwave photonic bandpass filter. When the output from the PD is fed back to the PolM, the OEO starts to oscillate and the oscillation frequency can be tuned by tuning the center frequency of the microwave photonic bandpass filter through tuning the optical wavelength. The optical comb is then generated by tapping part of the optical signal from the PolM and sending it to a second PolM. The joint operation of the two PolMs generates an optical comb with the comb spacing tunable by tuning the center frequency of the microwave photonic filter. Through introducing a second wavelength into the OEO, a duplicated optical comb at the second wavelength is generated. An experiment is performed. An optical frequency comb with tunable frequency spacing from 6.6 to 15.3 GHz and a tunable center wavelength from 1500 to 1580 nm is generated.**

***Index Terms*— Optical frequency comb, optoelectronic oscillator, phase-shifted fiber Bragg grating, polarization modulation.**

I. INTRODUCTION

OPTICAL frequency combs have numerous applications such as in optical communications [1], optical sensing [2], high accuracy optical metrology [3], all optical signal processing [4], and microwave photonic signal processing [5]. A number of approaches have been proposed for the generation of an optical frequency comb. An optical frequency comb can be realized based on recirculating frequency shifting in an erbium-doped fiber amplifier (EDFA) loop [1], [6]. When an injected light wave is circulating in the loop, a new comb line is generated due to the frequency shifting based on single-sideband (SSB) modulation after each circulation. However, only one comb line is generated in each circulation and the number of comb lines is limited by the noise accumulation. An optical frequency comb can also be generated by using a fiber or a semiconductor mode-locked laser [7], [8]. Despite that this approach can generate an optical comb with a wide spectral width, special measures are needed to stabilize the operation at the cost of a higher complexity. The limited tunability of the generated comb in terms of frequency spacing and center wavelength is another major limitation. External modulation of a continuous-wave (CW) laser source using a Mach–Zehnder modulator (MZM) or a phase modulator (PM) [9], [10], or a cascade of multiple MZMs and PMs [11]–[14], has also been proposed to generate an optical frequency comb, and has been considered as an attractive solution due to its simplicity and stability, in addition to the large comb spacing tunability and center wavelength tunability. However, a stable and high power external microwave source is always needed to drive the modulators.

In this letter, we propose and experimentally demonstrate an OEO-based optical frequency comb generator with a widely tunable center wavelength and comb spacing without using an external microwave source. In the proposed comb generator, an optoelectronic oscillator (OEO) is used to generate a microwave signal [15], [16]. The OEO consists of a polarization modulator (PolM), a phase-shifted fiber Bragg grating (PS-FBG) and a photodetector (PD). The joint operation of the PolM, the PS-FBG and the PD corresponds to a frequency-tunable microwave photonic bandpass filter with the center frequency determined by the interval between the wavelength of the light wave and the notch of the PS-FBG. When the output from the PD is fed back to the PolM, an OEO is formed. By tapping part of the optical signal from the PolM and sending it to a second PolM, an optical comb is generated. The comb spacing is tunable by tuning the center frequency of the microwave photonic filter. By introducing a second wavelength into the OEO, a duplicated optical comb at a different wavelength is generated. The proposed comb generator is experimentally evaluated. A flat-top optical frequency comb with tunable comb spacing from 6.6 to 15.3 GHz and a tunable center wavelength from 1500 to 1580 nm is demonstrated.

II. PRINCIPLE

The schematic of the proposed OEO-based optical frequency comb generator is shown in Fig. 1. A CW light wave

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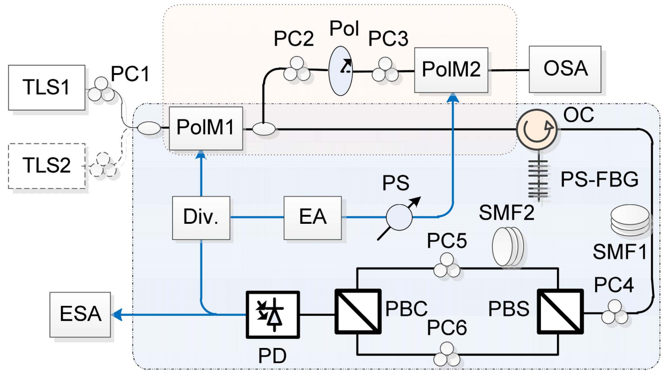

Fig. 1. Schematic of the OEO-based optical frequency comb generator.

from a tunable laser source (TLS1) is sent to a PolM (PolM1) via a polarization controller (PC1), to adjust the state of polarization (SOP) to have an angle of 45° relative to one principal axis of PolM1. A PolM is a special phase modulator that supports both TE and TM modes with opposite phase modulation indices [17]. The polarization-modulated signal at the output of PolM1 is then split into two parts by an optical coupler.

1) One part is sent to the PS-FBG through an optical circulator (OC). For both polarization directions, one of the sidebands is suppressed by the ultra-narrow notch in the PS-FBG. Therefore, the polarization-modulated signal is converted to an SSB intensity-modulated signal with two orthogonal components. The SSB signal passes through a section of single-mode fiber (SMF1) and is converted to an electrical signal at a PD, and then fed back to PolM1 via the RF port to form an OEO loop. As can be seen, the PolM1, the PS-FBG and the PD jointly operate as a frequency-tunable microwave photonic bandpass filter. To improve the phase noise performance and to reduce the side modes, two sub loops are incorporated in the OEO by using a polarization beam splitter (PBS), a section of SMF (SMF2) and a polarization beam combiner (PBC), with each sub loop traveling one of the two orthogonal SSB signals. Since the oscillation frequency of the OEO is determined by center frequency of the microwave photonic filter, which can be continuously tuned by controlling the interval between the wavelength of the light wave from TLS1 and the notch of the PS-FBG [18], the comb spacing of the generated optical frequency comb can thus be continuously tunable.

2) The other part is sent to a polarizer (Pol) through a second PC (PC2), which makes the principle axis of the Pol have an angle of 45° relative to one principle axis of PolM1. The joint operation of PolM1, PC2 and the Pol is equivalent to an MZM, with the bias point tunable by adjusting the static phase introduced by PC2. A second PolM (PolM2) is connected to the Pol via a third PC (PC3), through which one principal axis of PolM2 is aligned with the principal axis of the Pol. The microwave signal at the output of the PD is tapped via a power divider and then applied to PolM2 through an electrical amplifier (EA) and a phase shifter (PS). Thus, the two PolMs function as an MZM and a PM that are cascaded for optical frequency comb generation.

The proposed OEO-based comb generator can be extended to generate optical combs at multiple wavelengths. For example, when a second light wave at a different wavelength from TLS2 is sent to PolM1, as shown in Fig. 1, the optical frequency comb is duplicated at the new wavelength. It is worth noting that this scheme is only effective when the new optical frequency comb is not overlapped with the first optical frequency. In other words, the wavelength interval between the TLS1 and TLS2 must be large enough to avoid interference between the two optical frequency combs, to avoid the generation of beat tones between the two combs at the PD. In this case, the oscillation of the OEO is maintained by the master laser source (TLS1) and the introduction of a new optical wavelength will not change the operation of the OEO. Since the new wavelength can be arbitrarily tuned, the wavelength of the generated optical frequency comb can be tuned in a wide range. For applications where the original optical frequency comb is not needed, an optical band-stop filter at the output of PolM2 can be used to filter out the original optical frequency comb.

III. EXPERIMENTAL RESULTS AND DISCUSSION

An experiment is performed based on the setup shown in Fig. 1. The parameters of the major components in the experiment are given as follows: TLS1 (Yokogawa, AQ 2200-136) has a wavelength tunable range of 200 nm and a tuning step of 1 pm. TLS2 (Anritsu, MG 9638A) has a wavelength tunable range of 80 nm from 1500 to 1580 nm, a wavelength repeatability of 5 pm and a 1-hour wavelength drift of less than 100 MHz. The two PolMs (Versawave Technologies) have a 3-dB bandwidth of 40 GHz and a half-wave voltage of 3.5 V. The PS-FBG is fabricated in a photosensitive fiber using a uniform phase mask by scanning a UV beam at 244 nm along the fiber, and a π phase shift is introduced at the center of the grating by shifting the phase mask by half the corrugation width to generate an ultra-narrow notch. The center wavelength and the 3-dB bandwidth of the reflection spectrum of the PS-FBG are about 1549.52 nm and 0.48 nm, respectively. The 3-dB bandwidth of the ultra-narrow notch in the middle of the reflection spectrum is about 12 MHz, which is measured by an electrical vector network analyzer based on the optical SSB modulation technique [19]. The lengths of SMF1 and SMF2 are about 820 m and 550 m, respectively. The PD (u^2t, XPDV2150R) has a 3-dB bandwidth of 50 GHz and a responsibility of 0.65 A/W. The EA (Lucix, S060180P3401) has a bandwidth of 12 GHz from 6 to 18 GHz. The optical spectrum of the generated comb is measured by an optical spectrum analyzer (OSA, Ando AQ 6317B) with a resolution of 0.01 nm. An electrical spectrum analyzer (ESA, Agilent E4448A) is employed to monitor the electrical spectrum of the oscillating microwave signal.

The wavelength of TLS1 is first tuned at 1549.6 nm, which is 0.08 nm away from the center wavelength of the ultra-narrow notch of the PS-FBG, corresponding to a frequency separation of 10 GHz. Once the OEO loop is closed, microwave oscillation starts, and a microwave signal at 10 GHz is generated. Fig. 2(a) shows the electrical spectrum of the generated microwave signal at 10 GHz. A zoom-in view of the spectrum with a span of 500 kHz is shown as

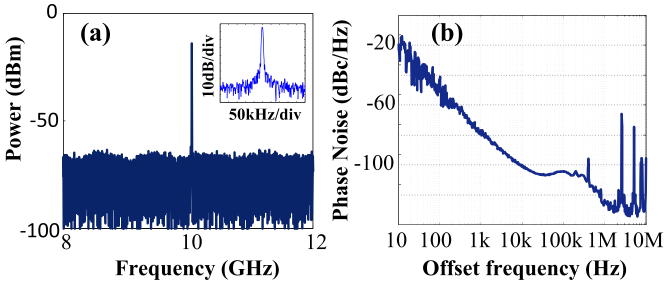

Fig. 2. (a) Electrical spectrum of the 10-GHz microwave signal. The inset gives a zoom-in view of the 10-GHz signal with a frequency span of 500 kHz. (b) Phase noise of the generated microwave signal.

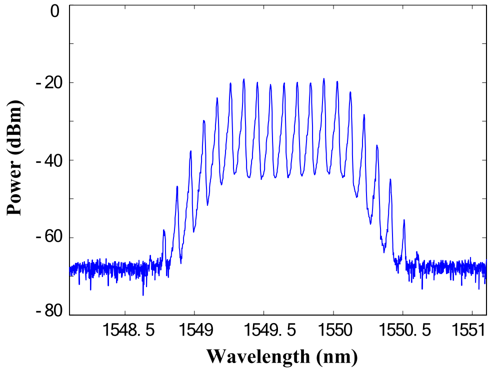

Fig. 3. Optical spectrum of the generated optical frequency comb with 10 GHz frequency spacing at the center wavelength of 1549.6 nm.

an inset in Fig. 2(a). Note that the frequency stability of the OEO depends on the wavelength stability of TLS1 and the stability of the notch of the unpackaged PS-FBG. TLS1 has a 24-hour wavelength drift less than 0.01 nm. In our experiment, a frequency drift of about 10 MHz is observed after an hour. For practical applications, the use of a wavelength-stabilized laser source and a well-packaged and temperature-controlled PS-FBG is necessary to increase the system long-term stability. To evaluate the quality of the generated microwave signal, the phase noise is measured. Fig. 2(b) shows the phase noise measurement, which is done by using a signal source analyzer (Agilent, E5052B) incorporating a microwave downconverter (Agilent, E5053A). As can be seen, the phase noise is -101.2 dBc/Hz at an offset frequency of 10 kHz. The phase noise performance can be improved if more sub-loops are incorporated in the OEO main loop, but at the cost of higher system complexity [20].

The optical spectrum of the generated optical frequency comb is shown in Fig. 3. The comb spacing is 10 GHz, which is equal to the oscillating frequency of the OEO. The flatness of the comb can be increased by adjusting the static phase introduced by PC2, to make the PolM-based MZM operate at the nonlinear regime. As can be seen, the optical frequency comb with a 1.5-dB bandwidth of 80 GHz, corresponding to 9 comb lines in the whole spectral width, is obtained. Note that a comb having a wider bandwidth with more comb lines can be achieved by increasing the power of the OEO oscillating signal applied to PolM2.

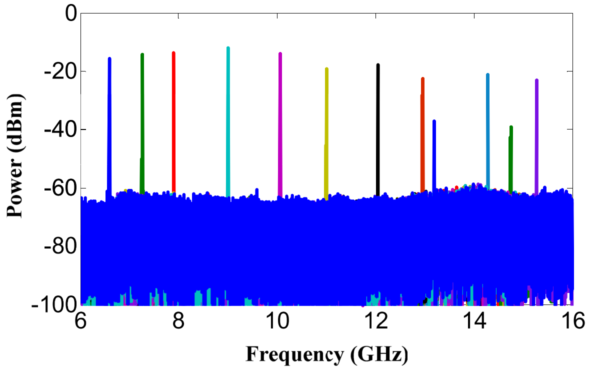

Fig. 4. Superimposed spectra of the oscillating microwave signal at different frequencies.

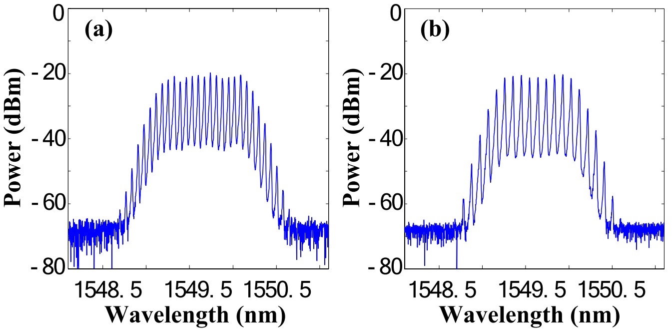

Fig. 5. Optical spectra of the optical frequency combs with a frequency spacing of (a) 8 GHz and (b) 12 GHz at the center wavelength of 1549.6 nm.

The tunability of the comb generator is then investigated. We first investigate the tuning of the comb spacing. By adjusting the wavelength of TLS1, the oscillating frequency of the OEO is tuned, and the frequency spacing of the comb is tuned. The wavelength of TLS1 can be tuned with a smallest tuning step of 1 pm, corresponding to a frequency spacing tuning step of about 125 MHz. Fig. 4 shows the superimposed spectra of the oscillating frequency with the frequency coarsely tuned from 7 to 15 GHz with a tuning step of about 1 GHz. Note that the tuning range of the frequency spacing is limited by the operating bandwidth of the EA in our experiment. Fig. 5 shows the optical spectra of the generated optical frequency combs with a frequency spacing of 8 GHz and 12 GHz. As can be seen, the comb flatness of the generated 15-line comb with a frequency spacing of 8 GHz is within 2.2 dB, while the comb flatness of the generated 9-line comb with a frequency spacing of 12 GHz is within 1.5 dB.

Then, the wavelength tunability of the comb is studied. To do so, a second wavelength from TLS2 is introduced. A duplicated optical frequency comb with a center wavelength at the second wavelength is generated. Fig. 6 shows six optical combs at different wavelengths from 1501.1 to 1576.5 nm with a wavelength interval of 15 nm. The comb spacing is set at 11 GHz. The flatness of the comb variation is within 1.5 dB. Clearly, the frequency spacing and center wavelength of our proposed optical frequency comb can be tuned independently.

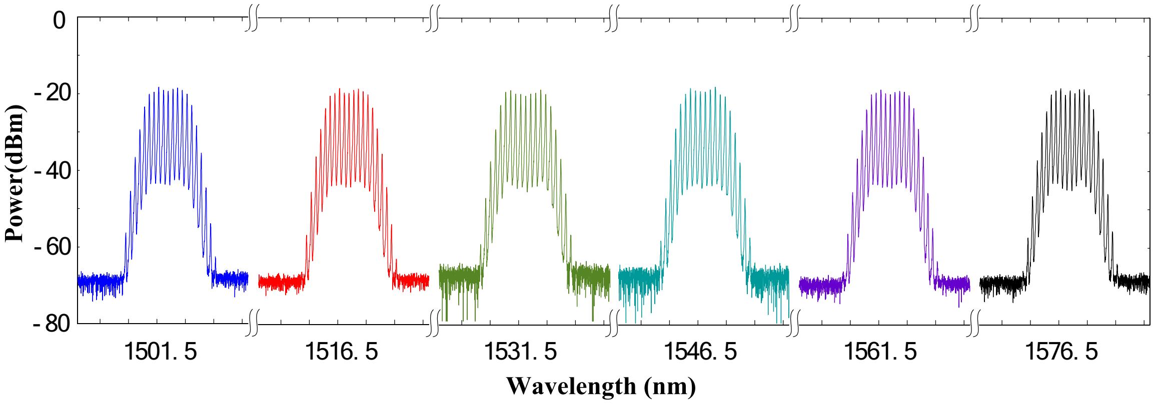

Fig. 6. Optical spectra of the generated optical frequency combs with a comb spacing of 11 GHz and a tunable wavelength from 1500 to 1580 nm.

IV. CONCLUSION

An OEO-based optical frequency comb generator with widely tunable frequency spacing and center wavelength was proposed and experimentally demonstrated. The main contribution of the work is the use of a PolM (PolM1) that performed two simultaneously functions, to serve as a PM to form a frequency-tunable OEO and to serve as an equivalent MZM to generate a frequency comb with a second PolM (PolM2). The comb spacing could be tuned by simply tuning the wavelength of TLS1. By introducing a second wavelength, the optical comb was duplicated at the new wavelength and the wavelength was arbitrarily tunable. The proposed OEO-based comb generator was experimentally investigated. A 15-line comb with a comb spacing of 8 GHz and comb flatness within 2.2 dB, and a 9-line comb with comb flatness within 1.5 dB were generated. The tunability of the comb spacing and the wavelength was also evaluated. In the experiment, a comb with tunable comb spacing from 6.6 to 15.3 GHz and a tunable wavelength from 1500 to 1580 nm was demonstrated.

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