Frequency- and Phase-Tunable Optoelectronic Oscillator

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***Abstract*— An optoelectronic oscillator (OEO) for the generation of a microwave signal with both tunable frequency and phase is proposed and experimentally demonstrated. In the proposed OEO, a single-sideband (SSB) polarization-modulated signal is generated by a polarization modulator (PolM) and a phase-shifted fiber Bragg grating (PS-FBG). The SSB polarization-modulated signal is then split into two parts. One part is sent to a photodetector (PD) and then fed back to the PolM to form the OEO loop. The other part is sent to an electronically tunable polarizer (ETP) and then applied to a second PD. The frequency tunability is achieved by tuning the wavelength of the optical carrier. The tunable phase is introduced by tuning the principal axis of the ETP. An experiment is performed, and a microwave signal with a tunable frequency from 6.6 to 13.1 GHz and a tunable phase from −180° to 180° is generated. The phase noise performance of the generated microwave signal is also evaluated, which is −101.9 dBc/Hz at an offset of 10 kHz.**

***Index Terms*— Microwave signal generation, microwave photonics, optoelectronic oscillator (OEO), polarization modulation.**

I. INTRODUCTION

OPTOELECTRONIC oscillators (OEOs) with the unique capability of generating high frequency and low phase noise microwave signals has been considered as an important microwave source for numerous applications, such as wireless communications, radar, warfare systems and modern instrumentation [1]–[3]. In general, the central frequency of an OEO is determined by an electrical bandpass filter (EBPF) in the loop. Therefore, the frequency tunability of the OEO is limited due to the narrow bandwidth of the EBPF. To achieve an OEO with a large frequency tunable range, a few techniques have been proposed. In [4], instead of using an EBPF, a Fabry-Perot laser diode (FP-LD) biased below the lasing threshold is used, thus the FP-LD can be considered as an ultra-narrow band optical filter and the frequency tuning of the OEO is achieved by changing the wavelength of the optical carrier. A frequency-tunable OEO can also be implemented based on the stimulated Brillouin scattering (SBS), in which the SBS gain spectrum with an ultra-narrow bandwidth is used for frequency selection. Again, the frequency tuning is achieved by changing the wavelength of the optical carrier [5]. Moreover, an OEO with tunable frequency can be performed using a tunable photonic microwave filter consisting of a polarization modulator (PolM), a chirped fiber Bragg grating (CFBG) and a polarization beam splitter (PBS). By adjusting the polarization direction of the PBS, the central frequency of the photonic microwave filter is shifted, and thus the oscillating frequency is tuned [6]. Recently, we proposed a frequency-tunable OEO with a large frequency tunable range using a phase modulator (PM) and a phase-shifted FBG (PS-FBG) [7]. The joint operation of the PM and the PS-FBG is equivalent to a microwave filter, with the central frequency tunable by changing the wavelength of the optical carrier [8]. For applications such as phased array beamforming [9] and array signal processing, a local oscillator (LO) array with tunable phase shifts is needed [10]–[12]. The OEOs proposed in [4]–[7] can have tunable frequency but with a fixed phase. Recently, a wideband microwave photonic phase shifter based on a PolM and a polarizer was demonstrated [13], but the microwave signal was generated by an independent microwave source.

In this letter, we propose and experimentally demonstrate, for the first time to the best of our knowledge, a microwave photonic system based on an OEO for microwave generation with both tunable frequency and phase. In the proposed OEO, a single-sideband (SSB) polarization-modulated signal is generated by a PolM and a PS-FBG. The SSB polarization-modulated signal is then split into two parts by an optical coupler. One part is sent to a photodetector (PD) and then fed back to the PolM to form an OEO loop. The other part is sent into an electronically tunable polarizer (ETP) and then applied to a second PD. The frequency tunability is achieved by tuning the wavelength of the optical carrier. The phase tunability is realized by electronically tuning the principal axis of the ETP. A microwave signal with a tunable frequency from 6.6 to 13.1 GHz and a tunable phase from −180° to 180° is generated. The measured phase noise performance of the

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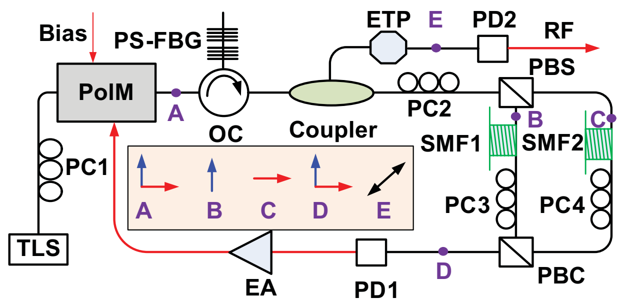

Fig. 1. Schematic of the proposed frequency- and phase-tunable OEO.

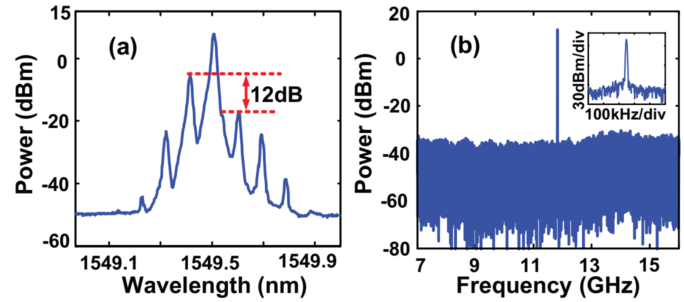

Fig. 2. (a) Optical spectrum of the SSB polarization-modulated signal. (b) Electrical spectrum of the 11.8-GHz microwave signal. The inset gives a zoom-in view of the 11.8-GHz signal with a frequency span of 500 kHz.

generated microwave signal is also evaluated. An SSB phase noise of −101.9 dBc/Hz at an offset of 10 kHz is obtained.

II. Principle

The schematic diagram of the proposed OEO is shown in Fig. 1. A light wave generated by a tunable laser source (TLS) is sent to a PolM via a polarization controller (PC1). The polarization direction of the light wave is adjusted by PC1 to have an angle of 45° relative to one principal axis of the PolM. The PolM is a special phase modulator that supports both the transverse-electric (TE) and transverse-magnetic (TM) modes with opposite phase modulation indices. The polarization-modulated signal is then sent to a 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. Thus, the polarization-modulated signal is converted to an SSB intensity-modulated signal with two orthogonal components. The electrical fields of the reflected signal along the two orthogonal directions are given by [13]

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix} = e^{j\omega_0 t} \begin{bmatrix} e^{j\pi/2}\left[J_0(\gamma) + jJ_1(\gamma)e^{j\omega_m t}\right] \\ J_0(\gamma) - jJ_1(\gamma)e^{j\omega_m t} \end{bmatrix} \quad (1)$$

where γ is the modulation index given by $\pi V_e/V_\pi$, V_e is the amplitude of the modulation signal, V_π is the half-wave voltage of the PolM, $J_n(\gamma)$ is the n^{th}-order Bessel function of the first kind, a static phase difference of $\pi/2$ between E_x and E_y is introduced by applying a DC bias to the PolM, and ω_0 and ω_m are the angular frequencies of the optical carrier and the generated microwave signal, respectively. Note that under small-signal modulation condition, only the carrier and the $\pm 1^{\text{st}}$ sidebands are considered in (1).

The SSB polarization-modulated signal reflected from the PS-FBG is split into two parts. One part is sent into a PD (PD1) to perform optical-to-electrical conversion. The electrical signal is then fed back to the PolM via the RF port to close the OEO loop. To increase the free spectral range (FSR) of the OEO loop, in the proposed OEO, we incorporate two sub loops, implemented by using a PBS, two single-mode fibers (SMFs) and a polarization beam combiner (PBC), with each sub loop traveling one of the two orthogonal modes.

Mathematically, the microwave signal at the output of PD1 is given by

$$i_1(t) \propto |E_x|^2 + |E_y|^2 \propto J_0(\gamma)J_1(\gamma)\sin(\omega_m t) \quad (2)$$

which is fed back to the PolM after amplified by an electrical amplifier (EA).

The other part of the SSB polarization-modulated signal with two orthogonal components from the optical coupler is sent to an ETP. The two orthogonal components are projected to the principal axis of the ETP. The photocurrent at the output of PD2 is given by [13]

$$\begin{aligned} i_2(t) &= R\left|E_x\cos\theta + E_y\sin\theta\right|^2 \\ &\propto J_0(\gamma)J_1(\gamma)\sin(\omega_m t + 2\theta) \end{aligned} \quad (3)$$

where R is the responsivity of PD2, θ is the angle between the principal axis of the ETP and one of the two principal axes (say, the x-axis) of the PolM. By tuning the principal axis of the ETP, the orthogonal components projected to the principal axis of the ETP will be changed, which leads to the tuning of the phase.

III. Experiment and Results

An experiment based on the configuration shown in Fig. 1 is carried out. A light wave at 1549.5 nm from the TLS (Anritsu MG9638A) is sent to the PolM (Versawave Technologies) via PC1. The PolM has a 3-dB bandwidth of 40 GHz. The PS-FBG is written in a photosensitive fiber with a uniform phase mask by scanning an UV beam along the fiber, and the phase shift is introduced at the center of the grating by shifting the phase mask by half the corrugation width. The 3-dB bandwidth of the reflection spectrum of the PS-FBG is about 0.48 nm, and there is an ultra-narrow notch in the middle of the reflection spectrum at about 1549.6 nm with the 3-dB bandwidth of 12 MHz. The length of SMF1 and SMF2 in the two sub loops are about 550 m and 820 m, respectively. Two PDs (New Focus 1014) with a bandwidth of 20 GHz are used. The bandwidth of the EA (Avantek SA82-0431) used is from 8 to 18.2 GHz. The phase tunability is performed by electronically tuning of the principal axis of the ETP (JDS Uniphase PR2000).

The optical spectrum of the signal reflected from the PS-FBG is measured by an optical spectrum analyzer (OSA), as shown in Fig. 2. As can be seen, the -1^{st} order sideband is suppressed, which is 12 dB lower than the $+1^{\text{st}}$ sideband. The SSB polarization-modulated signal is then split into two parts. One part is sent to PD1 via the two sub loops, and fed back to the PolM via the RF port after amplified by the EA. Once the loop is closed, microwave oscillation starts and a microwave signal is generated. Fig. 2(b) shows the electrical spectrum of the generated microwave signal at 11.8 GHz. A zoom-in view

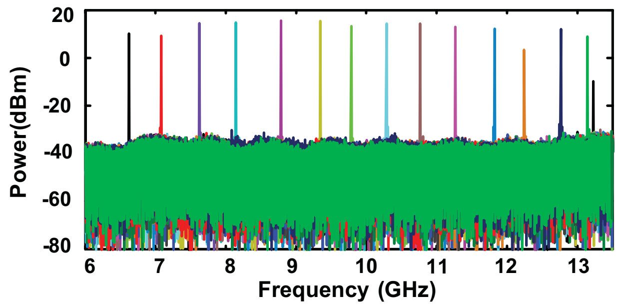

Fig. 3. Spectrum of the generated microwave signal at different frequencies.

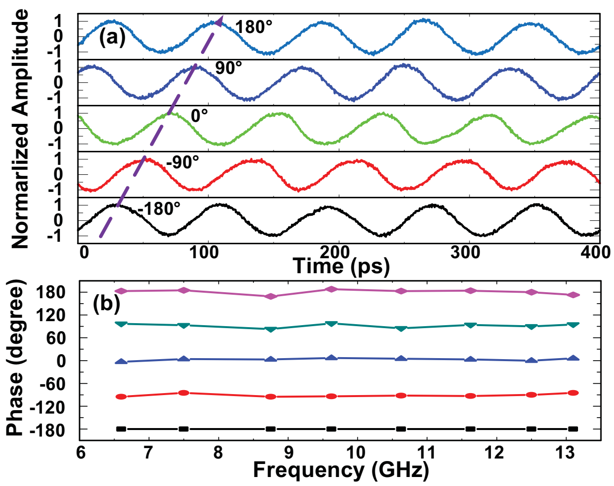

Fig. 4. (a) Generated microwave with different phase shifts. (b) Phase response of the generated microwave signal at different frequencies.

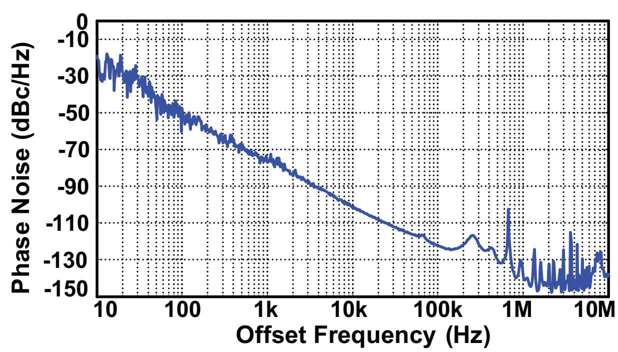

Fig. 5. SSB phase noise of the generated microwave signal.

of the spectrum with a span of 500 kHz is shown in the inset of Fig. 2(b).

The frequency tunability is first evaluated. By changing the wavelength of the TLS, the frequency of the microwave signal is shifted. A microwave signal, which is tunable from 6.6 to 13.1 GHz, is generated, as shown in Fig. 3. Note that the TLS has a wavelength tuning resolution of 1 pm, thus the oscillating frequency can be tuned at a step of about 125 MHz [7]. If a tunable optical delay line is incorporated into one of the loops, the oscillating frequency can be finely tuned [1].

Then, the phase tunability is investigated. The phase measurement is performed by using a sampling oscilloscope (Agilent DCA-J 86100C). As shown in Fig. 4, the phase can be shifted from −180° to 180° by tuning the principal axis of the ETP. As shown in Fig. 4(b), a constant phase shift over a frequency range from 6.1 to 13.1 GHz is obtained, thus the phase tuning is frequency independent. The small variations are due to the measurement errors.

The SSB phase noise of the generated microwave signal is measured by a signal source analyzer (Agilent E5052B), with the result shown in Fig. 5. As can be seen, the phase noise is −101.9 dBc/Hz at an offset of 10 kHz.

IV. Conclusion

An OEO with both tunable frequency and phase was proposed and demonstrated. The key of the technique was the use of the PolM in junction with the PS-FBG to generate an SSB polarization-modulated signal to maintain the oscillation of the OEO, and to introduce a phase shift with the help of an ETP. The proposed OEO was experimentally evaluated. A microwave signal with a frequency tunable range from 6.6 to 13.1 GHz and a phase tunable range from −180° to 180° was generated.

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