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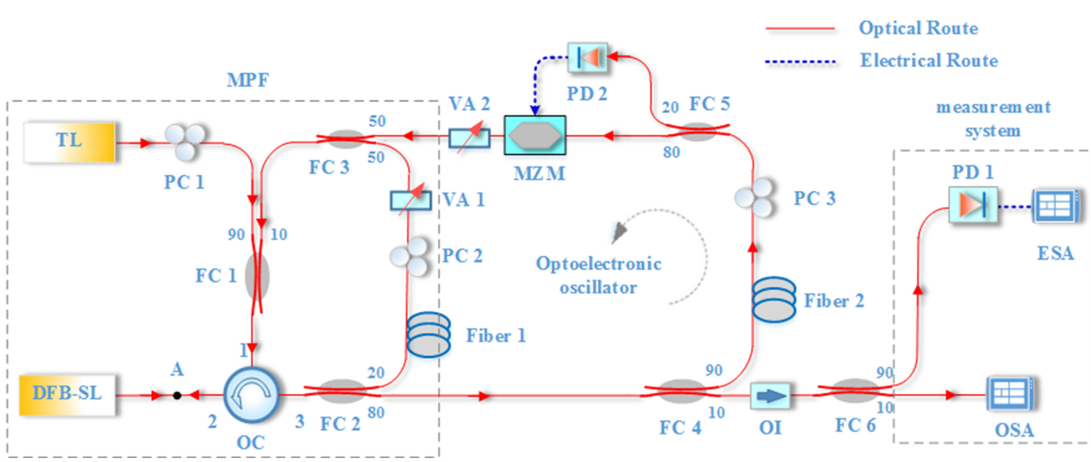

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Generation of Widely Tunable Narrow-Linewidth Photonic Microwave Signals Based on an Optoelectronic Oscillator Using an Optically Injected Semiconductor Laser as the Active Tunable Microwave Photonic Filter

Xiao-Dong Lin,[1] **Zheng-Mao Wu**,[1] **Tao Deng**,[1] **Xi Tang,**[1] **Li Fan,**[1,2] **Zi-Ye Gao**,[1] **and Guang-Qiong Xia**[1]

[1]School of Physical Science and Technology, Southwest University, Chongqing 400715, China
[2]School of Electronic and Information Engineering, Southwest University, Chongqing 400715, China

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Abstract: In this work, a novel optoelectronic oscillator (OEO) structure is proposed for generating widely tunable photonic microwave. In this structure, an optical injection semiconductor laser (OISL) functions as an active tunable microwave photonic filter (MPF). Through controlling the injection power and frequency detuning, the OISL is driven into period-one dynamics whose oscillation frequency can be widely tuned from 10.43 to 65.82 GHz. As a result, the OISL can be regarded as a widely tunable active MPF. By introducing an optical feedback loop, the filtered bandwidth of the widely tunable active MPF can be further reduced. Taking the OISL under optical feedback as a widely tunable narrow-bandwidth MPF and a seeding laser source to establish an OEO structure, widely tunable narrow-linewidth photonic microwave can be generated. The experimental results demonstrate that widely tunable photonic microwaves ranging from 10.43 to 39.10 GHz with linewidths below 0.1 MHz and phase variances below 10^{-2} (rad^2) can be achieved.

Index Terms: Photonic microwave, distributed feedback semiconductor laser (DFB-SL), optoelectronic oscillator (OEO), microwave photonic filter (MPF), optical injection, optical feedback, linewidth, phase variance.

1. Introduction

Photonic microwave has been widely applied in radio-over-fiber communications, radar, signal processing [1]–[3] etc. because of its unique advantages such as high-frequency, high-speed long-distance low-loss data transmission, immunity to electromagnetic interference, wavelength division multiplexing (WDM) capability [4]–[6]. A considerable number of schemes for generating photonic microwave have been proposed and developed, including direct current modulation [7], mode-locked laser [8], dual-mode laser [9], [10], optical heterodyne [11], [12], optoelectronic oscillator (OEO) [13], [14] etc. In the past years, the scheme based on OEO receives more attention since the generated photonic microwave signals possess extremely low phase noise, high stability and high spectral purity [13]. A conventional OEO is essentially an optoelectronic feedback loop, including a laser source, an intensity modulator (IM), a long fiber, a photodetector (PD), an electrical bandpass filter (EBPF) and an electrical amplifier (EA). When the loop gain is larger than the loss and the round-trip phase shift of signal is an integer multiple of 2π, the OEO will start to oscillate at one of its eigenmodes determined by the central frequency of the EBPF [14]. A very long fiber (high-Q cavity) is used to ensure a very low phase noise, but it also results in a small mode interval between two adjacent eigenmodes. Therefore, in order to ensure high spectral purity, a very narrow bandwidth ($\sim$MHz or below) EBPF is required to suppress the unwanted spurious modes. Generally, EBPF possesses a fixed central frequency, which limits the frequency tunable ability. In order to overcome this limitation, some approaches based on microwave photonic filter (MPF) have been proposed and demonstrated. In 2010, a MPF based on an optically injected Fabry–Perot laser diode was used in an OEO structure, and the frequency of the generated microwave can be tuned from 6.41 to 10.85 GHz by changing either the wavelength of the injection light or the lasing wavelengths of the FP-LD longitudinal modes [15]. In the same year, a phase modulator in combination with a linearly chirped fiber Bragg grating (FBG) was proposed to serve as MPF in an OEO, and a tunable frequency range from 6.5 to 11.5 GHz was realized [16]. In 2012, a MPF consisted of a finite impulse response (FIR) filter, which is formed by a broadband optical source and a multichannel filter, and a dispersion element was utilized in an OEO, and a tunable range of 9.7 GHz was achieved by changing either the channel spacing of the FIR or the chromatic dispersion of the dispersion element [17]. In the same year, by using a polarization modulator and a chirped FBG as a MPF, a tunable range from 5.8 to 11.8 GHz was reported by adjusting the polarization state of the light wave [18]. In 2015, through introducing an active MPF based on a self-injection-locked monolithic dual-mode amplified feedback laser (DM-AFL) in an OEO, tunable microwave outputs ranging from 32 to 41 GHz were realized [19]. Although these relevant investigations mentioned above demonstrated that the frequency of generated photonic microwave based on OEO can be tuned, the tuning range is still relatively limited.

In recent years, the nonlinear dynamical period-one (P1) oscillation of an optically injected semiconductor lasers (OISL) has attracted great interests due to its unique virtues [20]–[22]. First, the frequency of P1 oscillation can be far beyond the relaxation resonance frequency of the laser [23]. By simply adjusting the power and frequency of the injection light, the frequency of P1 dynamics can be continuously and widely tuned from a few to tens or even hundreds of gigahertz [24], [25]. Second, since the P1 dynamics shows an asymmetric optical spectrum caused by the anti-guidance effect of semiconductor laser [21], the output with single-sideband (SSB) spectrum distribution can be realized by properly controlling injection parameters, which is suitable for transmitting in Radio-over-Fiber (RoF) system [26]. Additionally, since two optical components of P1 oscillation co-exist inside the cavity of OISL, the P1 frequency is easily stabilized by some techniques including external injection locking [27], phase locking [28], optical feedback [29], [30] optoelectronic feedback [20], [31] and subharmonic locking [32].

Now that only the optical components locating at near two optical component peaks of P1 oscillation can obtain enough gain to be lasing and the other optical components are suppressed, an OISL operating at SSB P1 can be regarded as an active MPF. Through varying the injection power and frequency detuning, the frequency interval between the two optical components can be adjusted easily, namely the frequency of the MPF can be tuned. Furthermore, through introducing optical feedback, the bandwidth of the MPF can be narrowed. Therefore, the OISL under optical feedback may be a desirable MPF in OEO structure. Meanwhile, the output of the OISL under optical feedback can be used as a seeding laser source to pump the OEO, and then the CW laser source and electrical amplifier required in traditional OEO are no longer necessary.

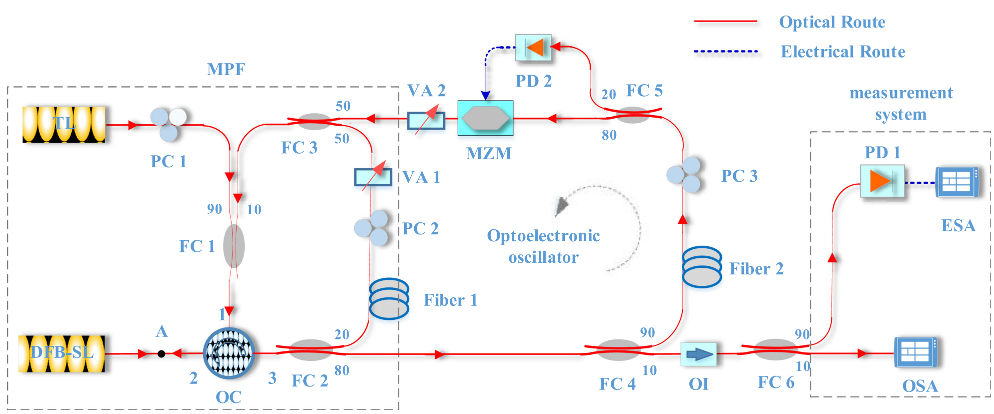

Fig. 1. Schematic of the experimental setup. TL: tunable laser; DFB-SL: distributed feedback semiconductor laser; VA: variable attenuator; FC: fiber coupler; PC: polarization controller; OC: optical circulator; OI: optical isolator; PD: photodetector; OSA: optical spectrum analyzer; ESA: electrical spectrum analyzer; MPF: microwave photonic filter.

Based on above considerations, in this work, we propose and experimentally demonstrate a novel OEO structure for the generation of widely tunable narrow-linewidth photonic microwave by using an OISL under optical feedback as an active MPF, and the linewidth and phase variance of generated photonic microwave are specified.

2. Experimental Setup

The schematic diagram of experimental setup is shown in Fig. 1. A commercial 1550-nm single-mode distributed feedback semiconductor laser (DFB-SL) under optical injection and optical feedback is taken as active tunable microwave photonic filter (MPF). The bias current and temperature of the DFB-SL are controlled by a high accuracy and low noise current-temperature controller (ILX-Lightwave, LDC-3724C). The injection light with a frequency of f_{inj} provided by a tunable laser (TL, Santec TSL-710, tuning range: 1480 nm–1640 nm, maximum output power: 20 mW) is injected into the DFB-SL after passing through a polarization controller 1 (PC 1), a 90:10 fiber coupler 1 (FC 1) and an optical circulator (OC) successively. The injection power P_{inj} can be adjusted through controlling the output power of TL, and it is characterized by the optical power tested at point A in Fig. 1. The frequency detuning $\Delta f\,(= f_{\text{inj}} - f_{\text{SL}}$, f_{SL} is the frequency of free-running DFB-SL) can be controlled through adjusting the frequency of injection light. PC 1 is used to match the polarization state of injection light with that of the DFB-SL. The optical feedback loop is composed of FC 2, 80 m Fiber 1, PC 2, variable attenuator 1 (VA1), FC 3, FC 1, and OC 2, whose role is to narrow the bandwidth of active tunable MPF.

In such system, the output of DFB-SL is divided into two parts by FC 2 after passing through OC. One part is sent to the measurement system after passing through FC 4 and optical isolator (OI) and FC 6. In the measurement system, a high-speed photodetector (PD1, U^2T-XPDV3120R, 70 GHz bandwidth) and an electronic spectrum analyzer (ESA, R&S FSW, 67 GHz bandwidth) are utilized to test the electrical spectrum of generated photonic microwave signal, and an optical spectrum analyzer (OSA, Ando AQ6317C, 0.015 nm resolution) is used to analyze the optical spectrum distribution. The other part is taken as a seeding resource to pump OEO, which is composed of 100 m fiber 2, PC 3, FC 5, high-speed photodetector 2 (PD 2, U^2T-XPDV2150R, 50 GHz bandwidth), and a 40 GHz Mach-Zehnder modulator (MZM) integrated an amplifier. The output of MZM returns to the DFB-SL via VA 2, FC 3, FC 1, and OC.

During the experiment, the DFB-SL is biased at 3.5 times of its threshold current (about 11.00mA), and its temperature is stabilized at 20.25 °C. Under these operating conditions, the free-running DFB-SL oscillates at 1553.32 nm (corresponding frequency $f_{\text{SL}} = 193.13$ THz) with an output power

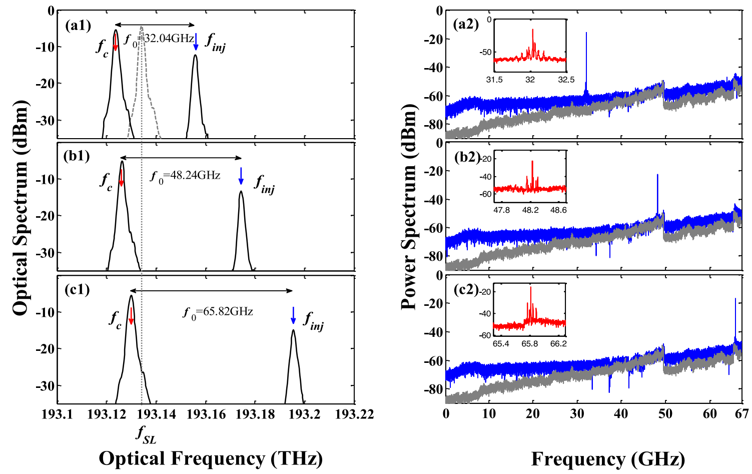

Fig. 2. Optical spectra and power spectra of the P1 oscillation for a DFB-SL (RBW: 1 MHz) subject to optical injection with the injection parameters of (a) (1.6 mW, 21.6 GHz), (b) (1.9 mW, 32.3 GHz), and (c) (3.0 mW, 61.4 GHz).

of 2.65 mW tested from fiber pigtail, and the relaxation resonance frequency of the laser is about 8.00 GHz.

3. Experimental Results and Discussion

3.1 Tunability of the MPF Based on OISL Operating at P1

First, we experimentally investigated the tunability of the MPF based on an OISL operating at P1 oscillation by disconnecting port 3 of OC. Fig. 2 displays the output optical spectra (left column) and power spectra (right column) under three sets of injection parameters. In this diagram, f_0 denotes the P1 frequency and can also be regarded as the central frequency of MPF. The grey dashed line and dotted line in optical spectra mark the optical spectrum and the central frequency (f_{SL}) of free-running laser, respectively. The grey curves in right column correspond to the noise floor of ESA. Under the optical injection with the injection parameters of (P_{inj}, Δf) = (1.6 mW, 21.6 GHz), (1.9 mW, 32.3 GHz), and (3.0 mW, 61.4 GHz), f_0 is 32.04, 48.24, and 65.82 GHz, respectively, and all the optical spectra possess single-sideband (SSB) distribution. It should be pointed out that, in order to ensure that the microwave signal is generated by the P1 oscillation but the beat between two free running lasers, we have adopted the method provided in Ref. [33] to discriminate firstly.

Furthermore, the overlapped power spectra of the OISL under multiple sets of injection parameters are shown in Fig. 3(a). Obviously, through selecting injection parameters, photonic microwave with different f_0 can be obtained. Fig. 3(b) shows the variation of f_0 with P_{inj} under different Δf. Although f_0 can only be adjusted within a relatively small range for a given Δf, it can be continuously tuned from 10.43 GHz to 65.82 GHz by selecting different Δf. In fact, via the optical spectrum analysis, it can be demonstrated that f_0 may be continuously tuned up to beyond 100 GHz. However, limited by the 67 GHz measured range of the used ESA, the characteristic of the generated microwave signal beyond 67 GHz cannot be analyzed.

3.2 Bandwidth Narrowing of the MPF Via Optical Feedback

Above results show that, using an OISL operating at P1 as a MPF, the frequency f_0 of the filter can be tuned within a large range. Besides the widely tunable ability, the narrow bandwidth is another key indicator for the MPF in OEO structure. From the insets in the right column of Fig. 2, it can be seen that the power spectra of the output from OISL operating at P1 possess irregular structures

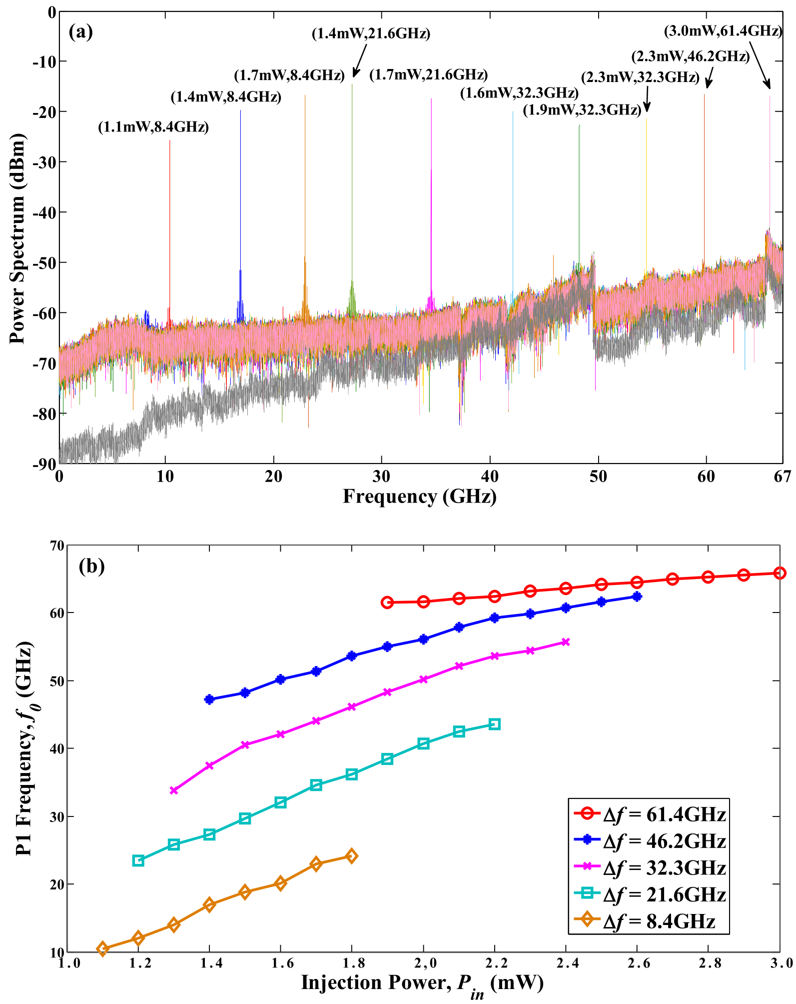

Fig. 3. (a) Overlapped power spectra of the OISL under multiple sets of injection parameters. (b) Variation of f_0 with injection power P_{inj} under different Δf.

because of frequency jitter. Therefore, for generating narrowly linewidth photonic microwave, the filtering feature of the OISL operating at P1 should be optimized. Based on this consideration, an optical feedback is further introduced to narrow the bandwidth of MPF by connecting port 3 of the OC and cutting off 80% port of the FC2. Since the power spectra output from the OISL generally possess irregular structures, the full width at half-maximum (FWHM, 3-dB linewidth) is not suitable to quantify the linewidth. In this work, we choose the standard deviation of the power distribution to denote the linewidth (Δv) of the output signal [20], which can be calculated by following formula

$$\Delta \nu = \left[\left\langle \nu^2 \right\rangle - \langle \nu \rangle^2\right]^{1/2}$$

where v denote the frequency, and

$$\langle \nu^p \rangle = \frac{\int_{-\infty}^{\infty} \nu^p P(\nu)\, d\nu}{\int_{-\infty}^{\infty} P(\nu)\, d\nu}, \quad (p = 1, 2)$$

Fig. 4 shows the power spectra output from the OISL without optical feedback (a) and with optical feedback (b) for the injection parameter set at (P_{inj}, Δf) = (2.0 mW, 21.6 GHz). Under this case, the central frequency f_0 is 39.10 GHz. Here, the number of data points included within frequency

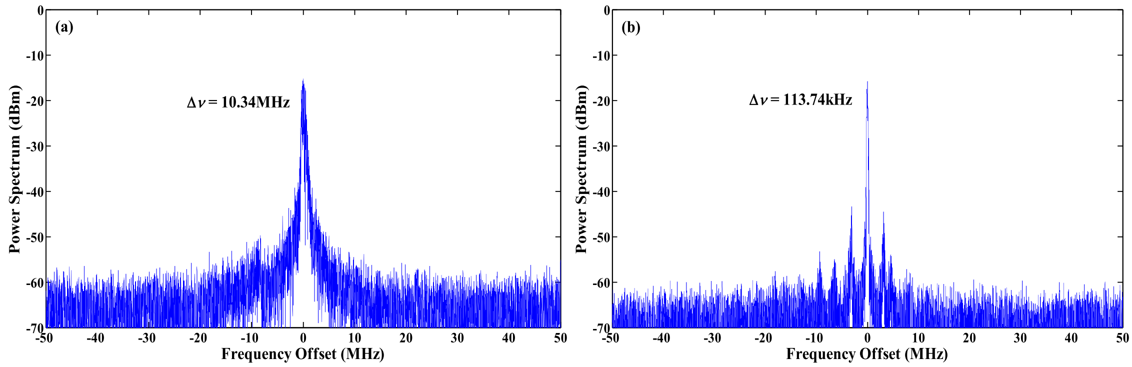

Fig. 4. Power spectra of the laser centered at the MPF central frequency $f_0 = 39.10$ GHz for the injection parameter of (2.0 mW, 21.6 GHz) under (a) no optical feedback (RBW: 1 MHz) and (b) optical feedback (RBW: 10 kHz).

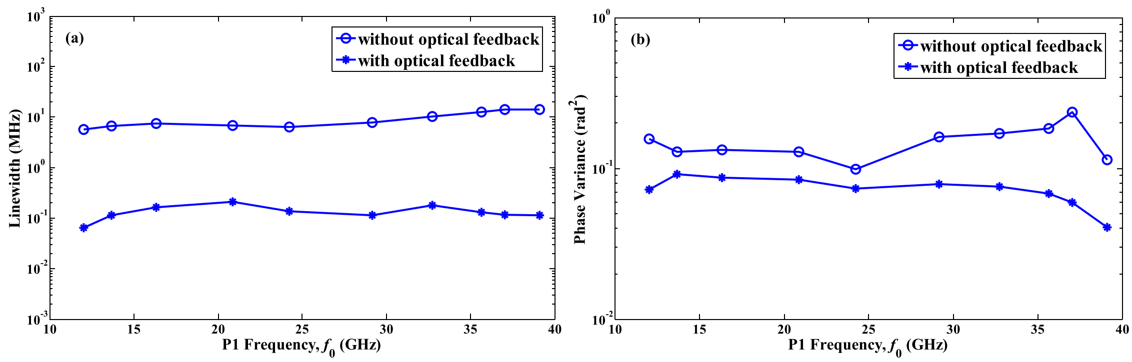

Fig. 5. (a) Linewidth and (b) phase variance at different f_0.

span of −50 MHz–50 MHz is set as 50000, which is enough for accurately estimating the linewidth via the formula. As shown in Fig. 4(a), without optical feedback, a relatively broad linewidth of 10.34 MHz is observed, which is slightly less than the linewidth of the microwave signal generated by heterodyning two lasers (TL and DFB-SL). However, after introducing optical feedback (as shown in Fig. 4(b)), the energy distribution is much more concentrated, and the linewidth is significantly reduced to 113.74 kHz, which is much less than that obtained by a simple heterodyne system. Observing Fig. 4(b) carefully, it can be found that two strong side peaks separated from the central peak by 3.18 MHz emerge in the power spectrum, which is originated from the optical feedback loop.

To further illustrate the narrowing effect of optical feedback, the linewidth and phase variance at different f_0 are given in Fig. 5, where the circles and the asterisks correspond to the case of the laser without and with optical feedback, respectively. The phase variance, which quantifies the frequency purity at f_0, is estimated by integrating the single sideband power spectrum normalized to the central peak from 3–50 MHz [30]. As shown in Fig. 5(a), the linewidth can be reduced about two orders of magnitude after introducing optical feedback, and meanwhile the phase variance is reduced slightly. The reason for relatively small decrease of phase variance may be due to side peaks emerging in power spectrum after introducing optical feedback.

3.3 Output Characteristics of OEO

Above experiments demonstrate that, two wavelength components can be oscillating simultaneously and the beat frequency f_0 between the two wavelength components can be adjusted in an

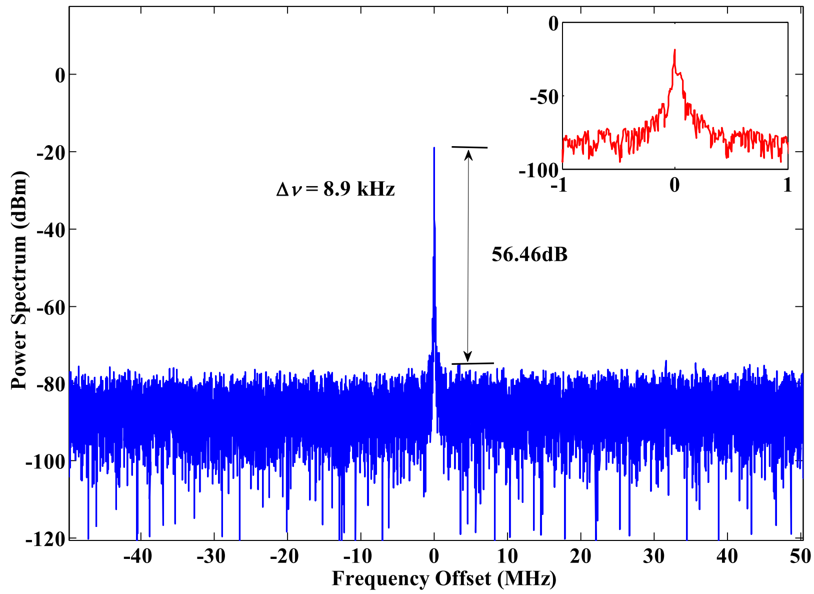

Fig. 6. Photonic microwave generated by OEO using OISL with optical feedback as the MPF, where the operating parameters are the same as those used to obtain Fig. 4(b). (RBW: 1 kHz).

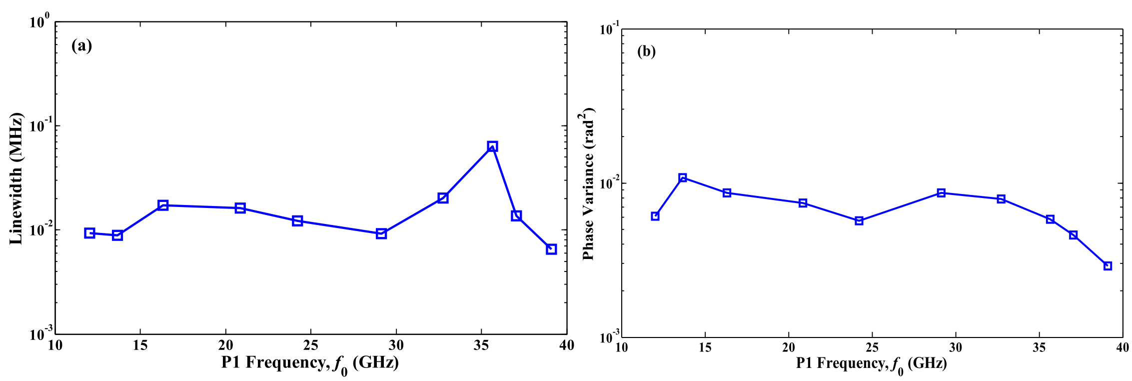

Fig. 7. (a) Linewidth and (b) phase variance of the photonic microwave operating at different f_0 generated by OEO.

OISL operating at P1 state. Moreover, after introducing optical feedback, the power spectrum output from OISL possesses narrow linewidth. Therefore, the OISL subject to optical feedback can be utilized as an active widely tunable narrow-bandwidth MPF. Meanwhile, the laser also plays a role of seeding laser source in OEO. Under suitable parameters, the OEO using OISL with optical feedback operating at P1 as the MPF can generate photonic microwave as shown in Fig. 6. Here, the operating parameters for OISL with optical feedback are the same as those used to obtain Fig. 4(b). Under this case, the central frequency of the photonic microwave is $f_0 = 39.10$ GHz, and the linewidth of the photonic microwave is about 8.9 kHz with a signal to noise ratio (SNR) of 56.46 dB.

Finally, the linewidth and phase variance of different f_0 microwaves generated by OEO are given in Fig. 7. From this diagram, it can be seen that, for the photonic microwave frequencies within the range of 10.43 GHz–39.10 GHz, the linewidths and phase variances are below 0.1 MHz and 10^{-2} (rad^2), respectively. For the photonic microwave with a frequency of 39.10 GHz, the phase variance is about 3×10^{-3} (rad^2) and the linewidth is about 8.9 kHz. Although the linewidth of the microwave signal generated by this scheme is still higher than that achieved with RF oscillator, the generated microwave signal possesses much better frequency-tunability. In particular, such proposed scheme can generate a photonic microwave signal, which can satisfy the need for transmitting microwave subcarriers through optical fibers [21].

4. Conclusion

A novel optoelectronic oscillator (OEO) configuration using an optical injection semiconductor laser (OISL) under optical feedback as an active tunable microwave photonic filter (MPF) is proposed for generating widely tunable narrow-linewidth photonic microwave. By adjusting the injection parameters, a widely tunable central frequency of MPF ranging from 10.43 GHz to 65.82 GHz is realized. By further introducing an optical feedback, the bandwidth of MPF is narrowed. Taking the OISL with optical feedback as a MPF and a seeding laser source to pump OEO, widely tunable photonic microwave ranging from 10.43 GHz to 39.10 GHz with the linewidth below 0.1 MHz and phase variance below 10^{-2} (rad^2) is generated. Though the highest frequency of generated photonic microwave is 39.10 GHz limited by the 40 GHz bandwidth of MZM used in this work, it is reasonable to predict that higher frequency photonic microwaves can be generated via this scheme after adopting larger bandwidth MZM.

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