High Resolution Brillouin Optoelectronic Oscillator using High-order Sideband Injection-locking

Mengyue Shi, Lilin Yi, *Member, IEEE*, and Weisheng Hu, *Member, IEEE*

***Abstract*—Microwave signals with high frequency, flexible tunability, and low phase noise are highly desired in signal processing and radar systems. In this paper, an optical injection-locking scheme using high-order phase modulation sideband is introduced to realize a stable Brillouin optoelectronic oscillator (OEO). Pure microwave signals up to 40 GHz with low phase noise are obtained using an electrical drive signal below 5 GHz. A flexible frequency tuning with high resolution of 8 MHz is maintained by controlling the electrical drive signal and the slave laser, and the side mode suppression ratio is higher than 60 dB. The phase noise of the OEO generated microwave signals under different master lasers is measured and compared to verify the significance of the master lasers with ultralow frequency noise. The maximum frequency drift of a 10.79 GHz signal is 1.4 kHz within 600 s, showing the stability of the proposed Brillouin OEO.**

***Index Terms*—Microwave Photonics, stimulated Brillouin scattering, optoelectronic oscillator.**

I. Introduction

In recent years, microwave photonics with the advantages of low loss, wide tunability, and immunity to electromagnetic interference, have attracted more and more attention to generate high-frequency microwave signals for communication or radar systems [1]. There are many schemes to generate microwave signals in the field of microwave photonics. Among those methods, a common way is to beat two different optical carriers extracted from two coherent signals or optical frequency combs (OFCs) [2]. Especially in [3], continuously tunable signals generation up to 110 GHz are reported by mixing the outputs of two injection-locked lasers utilizing an electrical reference signal below 4 GHz. But the purity of the generated microwave signal is limited by the reference, and there is a phase noise deterioration at high frequency due to frequency multiplications.

By contrast, optoelectronic oscillators (OEOs) can generate pure microwave signals with high frequency, low phase noise thanks to the high Q value, and have no phase noise deterioration at high frequencies [4]. Due to its intrinsic merits, there have been many OEO schemes [5]-[7]. In [5], stable microwave signals with high spectral purity are obtained based on parity-time symmetry principle. The generation of linearly chirped microwave waveforms using OEO also has been demonstrated [6], [7]. Usually, the main function of an OEO is a band-pass filter (BPF) with a narrow bandwidth to realize the mode selection, which can be either an electrical filter, or an optical filter. But the signal frequency tunability is also limited by those filters. By optical injection-locked to a Fabry-Perot laser diode method [8], using a reflective phase-shifted fiber Bragg grating (PS-FBG) [9], or an ultra-narrow electrical BPF [4], tunable microwave signals in a certain range can be realized. However, it is still a big challenge to simultaneously meet the requirements of wide tuning range, high tuning resolution, and high-frequency purity for OEO-based microwave generators.

Stimulated Brillouin scattering (SBS) effect having the inherent advantages of low threshold, narrow bandwidth, and flexible tunability is a promising optical filter to meet above BPF requirements [10]. However, the balance between the tuning range and resolution is still a considerable task. In our previous work, a Brillouin-based OEO equipped with both wide tuning range and high tuning resolution is achieved by extracting high-order phase modulation sideband as an optical pump signal through optical filtering [11]. However, the driving signal frequency must be high enough to maintain the sideband suppression ratio during the filtering process. An erbium-doped fiber amplifier (EDFA) is necessary to ensure sufficient pump power, which is a burden for the system. Therefore, an effective method to extract the pump signal from the phase modulation sidebands is preferred.

In this paper, a high-order phase modulation sideband injection-locking OEO (IL-OEO) scheme is proposed based on SBS. The SBS optical pump carrier extraction is realized by the IL process. The power and the sideband suppression ratio of the pump is mainly determined by the injection optical signal power and the slave laser (SL), so there is no need for an optical filter to select the wanted sideband, which reduces the system complexity and costs. Compared to the previous work, this method can significantly reduce the electrical drive signal frequency while maintaining a large sideband suppression ratio. It also solves the problem that the high-order sideband cannot be used due to its relatively low power in the previous work

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[11]. The influence of the master laser (ML) on the OEO generated signal phase noise is experimentally demonstrated. The side mode suppression ratio (SMSR) of the IL-OEO generated signal is higher than 60 dB. A precise frequency tuning can be realized by controlling the electrical drive signal with a frequency lower than 5GHz, and the tuning resolution is 8 MHz with a large tuning range up to 40 GHz. Since the SBS pump signal and the optical signal carrier are coherent, the frequency of the OEO obtained signal presents stable. Different as the pure IL-based coherent beating scheme in [3], the phase noise in the IL-OEO scheme keeps nearly the same for the generated signals, which is -116 dBc/Hz at 10 kHz offset frequency.

II. Experimental Setup And Analysis

The experimental setup to realize the SBS-based IL-OEO is shown in Fig. 1. The ML is a fiber laser (FL) operating at 1551.54 nm with a fixed power of 16.8 dBm and a linewidth of ~1 kHz. The continuous-wave light of the ML is split into two branches by a 90:10 optical coupler (OC). In the upper branch, to realize the SBS pump frequency shifting, ninety percent of the coupled output signal passes through a phase modulator 1 (PM1) with a 3 dB bandwidth of 20 GHz, which is driven by a microwave signal with a frequency below 5GHz. A series of sideband signals are generated by the PM1, and one of the sideband signals is sent into the SL after an optical circulator 1 (CIR1) as the injection-locking signal. The SL is a distributed feedback (DFB) laser around 1550 nm having a bandwidth of about 4 MHz without an isolator. By utilizing a high-order sideband signal injected to the SL as the SBS pump, the pump frequency can be several times of the electrical drive signal, which decreases the required drive signal frequency significantly. The optical SBS pump power is determined by the output power of the SL, so there is no need for an EDFA to compensate the pump power. The output of the locked SL with a power of 11.8 dBm propagates a 1 km high nonlinear fiber (HNLF) through a CIR2 as the SBS pump. A polarization controller (PC) is inserted before the CIR2 to maintain the maximum SBS gain. A dual-loop structure is involved in the feedback loop to suppress the side mode [11]. The output from the port3 of the CIR2 is sent into the dual-loop after a 50:50 OC, then passes through a single mode fiber (SMF) with a length of 1 km and 1.1 km respectively. Two photodiodes (PDs, u^{2}t XPDV2120RA) with a 3 dB bandwidth of 40 GHz are involved in the dual-loop respectively to realize the optical to electric conversion. The dual-loop outputs are combined together by an electrical coupler (EC) and then sent into the PM2 after passing through a low noise amplifier (LNA). Two broadband electrical filters at different band are used before the LNA separately to remove harmonics. One of the electrical filters has a pass-band from 5 GHz to 10 GHz used for generated signals between 5 GHz and 10 GHz, while the other one is from 10 GHz to 20 GHz. With these filters, the corresponding harmonics can be removed. The other signal branch of the ML passes through a PM2 with a 3 dB bandwidth of 40 GHz which is driven by the feedback signal of the OEO loop. The electric to optical conversion is realized by the PM2. After an isolator (ISO) and a PC, the PM2 output optical signal is sent into the HNLF and amplified by a SBS gain at 9.204 GHz offset from the pump. The SBS gain is used as an ultranarrow optical filter with a bandwidth of 30 MHz to realize the mode selection. The desired microwave signal can be observed at an electrical spectrum analyzer (ESA, Agilent N9010A) when the gain is higher than the loss in the loop, and the corresponding phase noise is measured by a phase noise analyzer (PNA, Microsemi 5125A). The generated microwave signal frequency is determined by the drive signal frequency and the sideband order, which can be expressed as $f_{OEO} = |\pm n f_{RF} - f_{SBS}|$, where f_{RF} is the frequency of the PM1 electrical drive signal, f_{SBS} is the Brillouin frequency shift, the - or + denotes the left or right sideband of the phase modulation signal in the frequency domain.

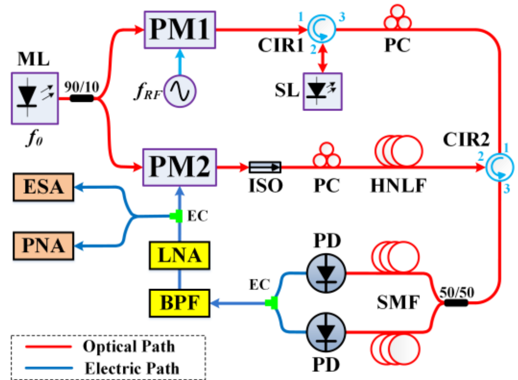

Fig. 1. Experimental setup of the IL-OEO based on SBS. ML, master laser; SL, slave laser; PM, phase modulator; CIR, circulator; PC, polarization controller; ISO, isolator; HNLF, high nonlinear fiber; SMF, single-mode fiber; PD, photodiode; EC, electrical coupler; BPF, band-pass filter; LNA, low noise amplifier; ESA, electrical spectrum analyzer; PNA, phase noise analyzer.

The phase noise of the obtained microwave signals mainly comes from the relative intensity noise (RIN) of the ML, SL via SBS amplification, chromatic dispersion, and optical interference due to facet reflection, flicker noise of the amplifier, thermal noise, shot noise and the loop jitters [10]. In this scheme, the ML and the SL are coherent through injection-locking. The phase noise of the electrical drive signal has no influence on the obtained signal as demonstrated in our previous work [11]. So the laser introduced noise mainly comes from the ML. The additive phase noise induced by the ML via chromatic dispersion can be expressed as [12], [13]

$$S_{CD}(f) = \frac{1}{2}\left(\frac{2\pi f_{OEO}\lambda_0^2 DL}{c}\right)^2 \cdot S_s(f), \qquad (1)$$

where λ_0 is the ML center wavelength, D is the chromatic dispersion coefficient, L is the loop length, $S_s(f)$ is the power spectral density of the optical frequency noise for the ML. The additive phase noise contributed by the ML via a double reflection process between the PD facet and the fiber connector of the PD can be described as [14]

$$S_{interference}(f) = 2r_c \cdot r_{PD} \cdot \sin^2(2\pi f_{OEO}\tau_d)\frac{\sin^2(\pi f \tau_d)}{f^2} \cdot S_s(f), \qquad (2)$$

where r_c and r_{PD} are the optical return loss of the fiber

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connector and the PD face respectively, τ_d is the round trip time of the double reflection process. Refer to (1) and (2), we can see the laser-induced noise mainly comes from the optical signal carrier, so an ML with high-stable frequency is required. Compared to using two separate lasers as the signal carrier and the pump respectively, this scheme can reduce lasers involved noise and improve the loop stability.

III. Experiment Results

The flexible frequency tunability and phase noise of generated signals are measured and analyzed. Set the electrical drive signal to be 5 GHz, the SL output optical signal after injection-locked to the 3rd order right sideband is shown in Fig. 2(a). The sideband suppression ratio is higher than 40 dB, and the sideband signal power is around -40 dBm, which is much lower than the SBS threshold, therefore can be neglected. To verify the influence of the ML on the phase noise of OEO generated signals, in addition to the FL described above, a DFB laser with a center wavelength of 1550 nm and a bandwidth of 1 MHz is also used as the ML. The single sideband (SSB) phase noise of the direct beating signal of the ML and the injection-locked SL is shown in Fig. 2(b). The SL is injection-locked to the 3rd order right sideband. The beating signal-1 with the red line is the beating signal of the FL and the injection-locked SL, while the beating signal-2 with the black line is the beating signal of the DFB laser and the injection-locked SL. The frequency of the beating signal-1 and 2 are both 15 GHz, and the SSB phase noise is -100 dBc/Hz and -75 dBc/Hz at 100 kHz offset frequency, respectively. The phase noise of the OEO generated signals when the FL and the DFB laser are used as the ML respectively is measured as shown in Fig. 2(b). The SSB phase noise of the corresponding OEO generated signals at 5.8 GHz is - 120 dBc/Hz and - 110 dBc/Hz at 100 kHz offset frequency when the FL and the DFB laser are used as the ML respectively. The peaks between the offset frequency of 1 kHz and 100 kHz come from the mode hopping of the ML. So a high phase noise of the ML will lead to a phase noise deterioration of the OEO generated signal. Compared to the directly beating method based on the injection-locking scheme, the phase noise can be significantly reduced using the IL-OEO scheme.

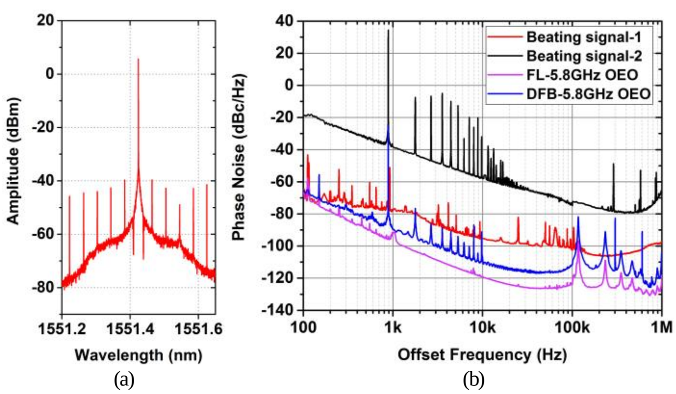


Fig. 2. (a)The optical spectrum of the SL output after injection-locked to the 3rd order right sideband with a 5 GHz electrical drive signal. (b) SSB phase noise of the coherent beating signal of the ML and the SL injection-locked to the 3rd order sideband when an FL and a DFB laser is used as the ML, respectively. And the SSB phase noise of the corresponding OEO generated signal with an FL and a DFB laser acted as the ML, respectively.

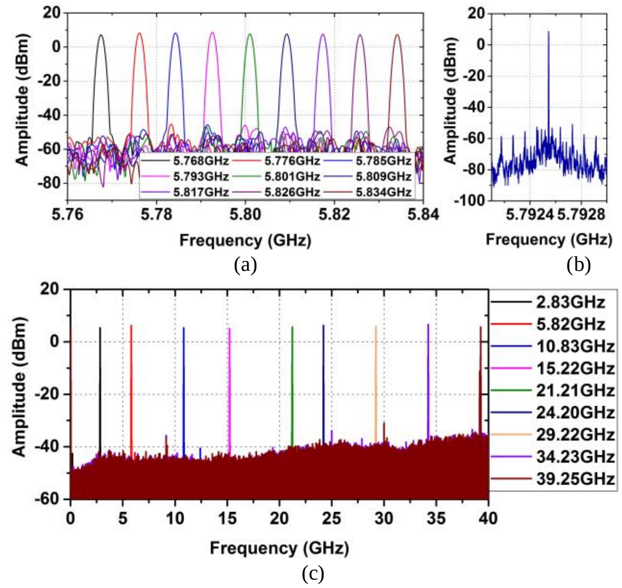
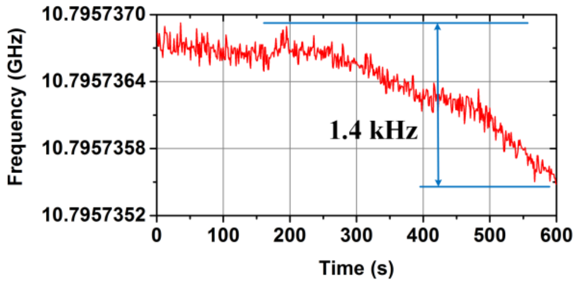


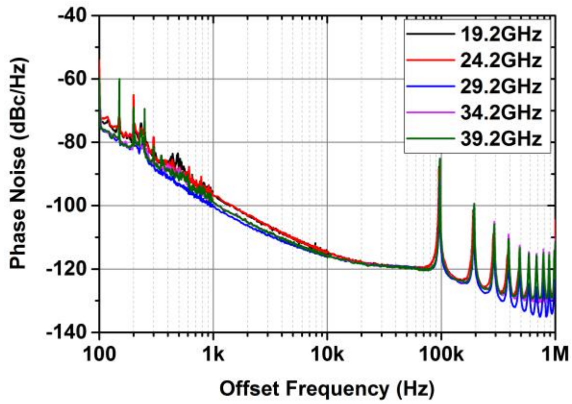
Fig. 3. (a) Electrical spectrum of the output signal based on IL-OEO from 5.768 GHz to 5.834 GHz with a tuning step of 8 MHz. (b) The zoom-in electrical spectrum of an OEO generated signal at the frequency of 5.7925 GHz. (c) Electrical spectrum of the IL-OEO generated signal with a wideband frequency tuning range up to 40 GHz.

The OEO obtained signal when the SL is injection-locked to the 3rd order right sideband with a 5 GHz electrical drive signal is 5.801 GHz. When the drive signal is tuned around 5 GHz with a tuning step of 2 MHz, the electrical spectrums of the OEO generated signals are shown in Fig. 3(a). The tuning step of the obtained signal is 8 MHz. Ideally, the frequency tuning step of this scheme is only determined by the drive signal frequency and the modulation order. In fact, the mode within the SBS gain bandwidth may oscillate once meets the oscillation requirements. It is possible to oscillate in different modes not exactly at the peak SBS gain point. This is the minimum tuning step achieved in this scheme, so the frequency tuning resolution is 8 MHz. The zoom-in electrical spectrum of the OEO generated signal at 5.7925 GHz is described in Fig. 3(b). The resolution bandwidth (RBW) of the ESA is set to be 1 kHz, and the SMSR is higher than 60 dB. So the single mode oscillation is maintained. The minimum frequency obtained in this scheme is 0.8 GHz when the SL is injection locked to the 2nd-order right sideband with a 5 GHz driving signal. The center wavelength of the SL can be roughly tuned by the temperature, and precisely tuned by the current with a tuning range of 4 nm. By controlling the PM1 drive signal and the SL wavelength, the SL can maintain injection-locked to the ML to generate stable OEO signals in a large range. The frequency tuning range of this scheme is up to 40 GHz as shown in Fig. 3(c), which is limited by the bandwidth of the devices such as the PM, PD, and LNA. And the RBW of the ESA in Fig. 3(c) is 1 MHz.

To measure the phase noise, the OEO signal is down-converted by mixing with a reference signal, then is sent into the PNA. A microwave source with ultra-low phase noise is used to generate the reference signal. In this way, the phase noise of the mixed signal just represents the phase noise of the OEO generated signal. The frequency fluctuation and the SSB phase noise of the OEO generated signals are shown in Fig. 4.



(a)



(b)

Fig. 4. (a) Frequency fluctuation of the proposed OEO generated signal at the frequency of 10.79 GHz. (b) SSB phase noise of the OEO generated signals at different frequencies.

The total measurement time is 600 s, and the measurement time interval between two adjacent samples is set to 1 s. The obtained signal frequency shows a long-term slow drifting. The maximum frequency drift of a 10.79 GHz OEO generated signal is 1.4 kHz. The SSB phase noise of the OEO generated signals at different frequencies is -116 dBc/Hz at 10 kHz offset frequency as shown in Fig. 4(b). The phase noise curves show consistency at different frequencies and have no phase noise deterioration at high frequencies, which is significantly different with the directly beating scheme in [3]. The phase noise difference at low offset frequency mainly comes from the loop jitters. This scheme also avoids extra signal frequency drift induced by the lasers in the two-laser scheme. Because the ML and SL signals are coherent in this scheme, the frequency fluctuations between the lasers can be ignored, and the slow frequency shift is mainly influenced by the temperature drift and loop jitters, which can be compensated by a phase-locking loop, and the loop stability also can be improved in this way.

TABLE I
PERFORMANCE COMPARISON OF TYPICAL OEO SCHEMES

Scheme	Frequency range (GHz)	Tuning resolution	SSB Phase noise (dBc/Hz@10kHz)
FP laser with optical injection [8]	6.41-10.85	~20 MHz	-92.8
Phase-shifted fiber Bragg grating [9]	3-28	125 MHz	-102
SBS gain [10]	DC-60	~2 GHz	-100
Our scheme	0.8-40	8 MHz	-116

A performance comparison between several typical OEO schemes and our proposed scheme is shown in Tab. 1. It is obviously seen that our proposed scheme has a relatively large frequency tuning range with a high tuning resolution.

IV. CONCLUSION

In conclusion, using a high-order sideband IL, a SBS-OEO with wide tuning range up to 40 GHz can be obtained which is over 8 times of the electrical drive signal frequency. The minimum tuning resolution is 8 MHz with an SMSR higher than 60 dB. The SSB phase noise of the generated signals at different frequencies is -116 dBc/Hz at 10 kHz offset frequency, and there is no phase noise deterioration using high-order sideband IL. This scheme avoids the phase noise degradation due to frequency multiplication in the directly coherent beating scheme. Since the pump signal and the optical signal carrier are coherent, the lasers-induced frequency difference can be reduced, which can improve the stability of the obtained OEO signal to generate microwave signals meet with communication needs.

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