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# RF Multiplier Based on Harmonic-Locked SMFP-LD and OEO Structure

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**ABSTRACT** We propose and experimentally demonstrate an RF signal multiplier based on optical injection locking in a semiconductor laser followed by an optoelectronic oscillator (OEO). In the proposed scheme, the modulated master laser is injected into a slave laser, a single mode Fabry-Pérot laser diode (SMFP-LD), in such a way that one of the harmonics of the modulated beam is locked to the corresponding mode of the SMFP-LD. By optical beating at the output of the SMFP-LD, stable multiple RF signals with a high signal-to-noise ratio (SNR) are generated due to SMFP-LD, which provides a sufficient gain to the RF signal. Further, we employ an OEO structure at the output of the SMFP-LD to optimize one of the generated multiple RF signals which are determined by the electrical bandpass filter (EBPF) and the low noise amplifier (LNA) in the OEO loop. As the gain of the OEO loop is higher than the loss, a high-purity oscillating signal, which is the selected multiple RF frequency, can be generated. In the experiment, a sextuple frequency (20 GHz) of the modulated signal is observed with an SNR and the phase noise of 54.44 dB and  $-102.44$  dBc/Hz@10 kHz, respectively. Compared with other photonic schemes, the proposed method provides high SNR, higher multiplication factor, and low phase noise.

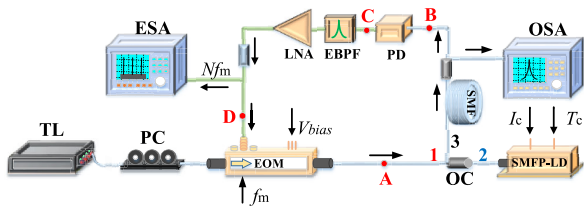
**INDEX TERMS** Optical injection, linear frequency modulation, SMFP-LD, red-shift.

## I. INTRODUCTION

High-frequency microwave and millimeter-wave signals have wide applications in many fields, such as radar, wireless communication, spectroscopy, military communications, and sensors [1]–[8]. The ability to generate high-quality microwave signals is a critical issue that needs to be solved for implementing them into practical applications. The traditional electrical methods employ a cascaded frequency doubling structure to generate a high-frequency RF signal, which increases the system loss and complexity, deteriorates the quality of the RF signal, and is affected by electromagnetic interference. In contrast, RF signal generation by optical methods has several advantages such as wide bandwidth, low phase noise, simple structure, and immune to electromagnetic interference [1], [2]. Several researchers have reported the generation of RF signals by the optical beating of two lasers with different wavelengths. However, the generated RF signal has high phase noise and low stability due to the

weak coherence of the lasers [9]. To improve the coherence, three technologies have been proposed: (1) optical beating of dual-wavelength laser or mode-lock laser to generate a high-quality RF signal [10]–[12], but it is complex in structure and has a high cost; (2) photonics-based frequency multiplier in which external modulation is used to obtain high-order harmonics with high coherence [1], [13]–[15], however, due to the inherent power loss of the high-order harmonics and limited biasing voltage of the modulators, the multiple frequencies generated by beating the modulated beam have a limited range; (3) locking the phase difference of the lasers to generate a high-quality RF signal, including optical injection locking (OIL) [16], [17], optical phase-locked loop (OPLL) [18], [19] and optical injection phase-locked loop (OIPLL) [20], [21]. The RF signal generated by combining the optical injection locking with phase-locked loop exhibits less linewidth, high power, and low phase noise. However, the complicated structure, high cost, and instability in frequency and power of the generated RF signal need to be solved. Except for the optical beating method for RF signal generation, the optoelectronic oscillator (OEO) structure has

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**FIGURE 1.** Experimental setup of the proposed harmonics locked RF multiplier with an optoelectronic oscillator. TL: tunable laser; PC: polarization controller; EOM: electro-optic modulator; OC: optical circulator; SMFP-LD: single mode Fabry-Pérot laser diode; SMF: single mode optical fiber; PD: photoelectric detector; EBPF: electrical bandpass filter; LNA: low noise amplifier; OSA: optical spectrum analyzer; ESA: electrical spectrum analyzer.

been widely investigated to generate a high-quality RF signal/RF signal multiplier. The OEO, reported by X. Yao *et al.* works as a microwave oscillator using optical devices to store energy [22]. In the OEO structure, if the gain of the OEO feedback loop is higher than the loss, the OEO starts to oscillate at one of its Eigenmodes which is determined by the center frequency of the electrical bandpass filter in the OEO loop. As a result, a high-frequency signal with high spectral purity is generated [23], [24]. The photonic methods of RF signal multiplier reported are mainly based on cascading one or more Mach-Zehnder Modulators (MZM) and driving them by RF signal while properly setting the bias voltage of the modulator [15], [25], [26]. Even though the cascaded modulator or DP-MZM are used, the signal quality, such as signal-to-noise ratio (SNR) and phase noise, of the multiple RF is not significantly improved. In addition, the complex modulator structure such as DP-MZM, cascaded MZM, has a complicated structure and working parameters.

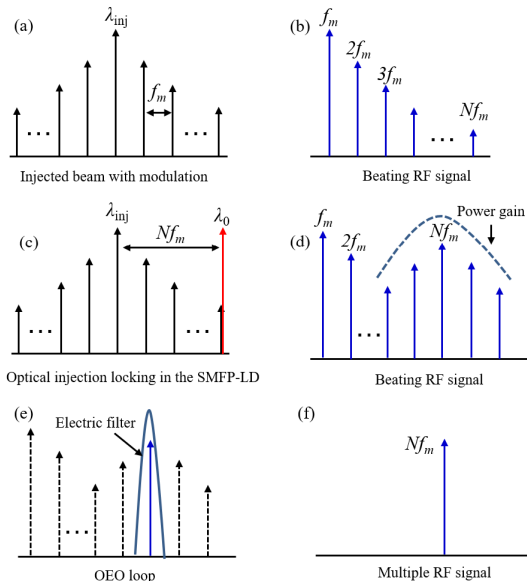
In this paper, we combine optical injection locking with an OEO structure to realize an RF signal multiplier. Optical injection to the semiconductor laser is a simple way to generate a microwave signal. In order to phase-lock the injected beam and the corresponding mode of the semiconductor laser, we modulate the injected beam in such a way that one of the harmonics is locked to the corresponding mode of the semiconductor laser. The locked harmonics of the modulating signal is amplified due to the power gain of the semiconductor laser, and hence a stable RF signal with low phase noise is generated. It is worth mentioning that the semiconductor laser we used for the experiment is a single mode Fabry-Pérot laser diode (SMFP-LD), which is a modification of the conventional FP-LD with an external cavity [25]. The use of SMFP-LD provides flexibility on a wide range of wavelengths of the external beam because the external beam can be injected into any of the modes, unlike in DFB lasers. Further, we use the OEO feedback loop to improve the quality of the generated RF signal. We generate an RF signal of 20 GHz by folding six times the modulating frequency with an SNR of 54 dB and the phase noise of  $-102.44$  dBc/Hz@10 kHz.

## II. BASIC OPERATING PRINCIPLE

The basic experimental setup of the proposed frequency multiplier based on harmonic injection locking in the SMFP-LD

followed by the OEO structure is shown in Fig. 1. The optical beam generated from a tunable laser (TL) is injected into an SMFP-LD through a polarization controller (PC), an electro-optic modulator (EOM), and an optical circulator (OC). The SMFP-LD used in the experiment comprises a multi-mode FP-LD with a built-in external cavity that provides a single longitudinal mode. Due to the Vernier effect of the external cavity, the SMFP-LD has a dominant mode with the side mode suppression ratio (SMSR) of more than 34 dB and tunability of more than 10 nm, which is attained by controlling the operating temperature and the biasing current [27]. The EOM used in the proposed RF multiplier is 40 Gbps LiNbO<sub>3</sub> Mach-Zehnder Modulator (FUJITSU FTM7938EZ), which has a 3 dB optical bandwidth  $\geq 25$  GHz. The PC controls the polarization state of the injected beam because the injection locking in SMFP-LD only works in the TE mode, and with TM mode null position is observed, which is known as absorption locking. In the experiment setup, EOM modulates the injected beam with a modulating frequency of  $f_m$  to generate high-order harmonics. The modulated optical beam is injected into the SMFP-LD in such a way that injected beam has a negative wavelength detuning (the wavelength of the injected beam is lesser than that of the corresponding mode in the SMFP-LD), and one of the harmonics is locked to the corresponding mode of the SMFP-LD. The output of the SMFP-LD is fed to a photoelectric detector (PD) via a single mode optical fiber (SMF) with a length of 1015 m. The RF signal generated through optical beating is fed back to the EOM to form an OEO structure through a low noise amplifier (LNA) and an electrical bandpass filter (EBPF). The EOM in the OEO loop has two primary functions: (1) convert the electric RF signal to optical domain by modulating the RF signal generated in the PD, (2) generate high-order harmonics of the external RF signal for frequency multiplier by modulating external RF signal. The output characteristics of the proposed multiplier are analyzed by using optical spectrum analyzer (OSA), and electrical spectrum analyzer (ESA) in the optical and electrical domain, respectively.

The basic principle of the RF multiplier using harmonics locked optoelectronic oscillator is shown in Fig. 2. Figure 2(a) shows the optical spectrum after the modulation of the injected beam ( $\lambda_{inj}$ ) with a modulating frequency of  $f_m$ . The corresponding electric spectrum after the optical beating of the modulating beam in PD is shown in Fig. 2(b). We observe that with a small-signal modulation, RF signals, which are multiples of  $f_m$  are generated. However, RF signal with higher frequency has a weak signal-to-noise ratio (SNR) and significant phase noise. To improve the SNR and the phase noise of high-frequency RF signals, optical injection of the modulating beam to an SMFP-LD is employed. Optical beams generated in Fig. 2(a) are injected into an SMFP-LD in such a way that  $\lambda_{inj}$  has negative wavelength detuning, and one of the harmonics of the modulating beam (the  $+N^{\text{th}}$  harmonics) is locked either to the dominant mode ( $\lambda_0$ ) or to the corresponding side mode of the SMFP-LD. Figures 2(c) and 2(d) show the optical spectrum and electric spectrum



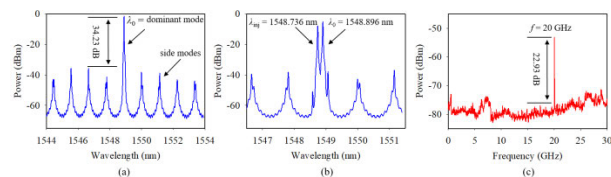
**FIGURE 2.** Illustration of the principle of the proposed frequency multiplier (a) optical spectrum of an injected beam with modulation, (b) the electric spectrum of (a) through optical beating, (c) optical spectrum of the SMFP-LD after optical injection, (d) the electric spectrum of (c), (e) output of OEO loop, (f) the RF signal (multiple of modulating frequency,  $f_m$ ) generated by optical injection and OEO.

output after optical injection of the modulating beam in the SMFP-LD, respectively. Due to the  $N^{\text{th}}$  harmonics locked to the corresponding mode, the output signals have a power gain. Further, to obtain a single high purity multiplier signal ( $Nf_m$ ), the multiplier signal ( $Nf_m$ ) selected by an EBPf and amplified by an LNA is fed back to EOM, thus, forming an OEO loop. The schematic of the spectrum output after the OEO loop of the proposed scheme of the RF generator is shown in Fig. 2(e) and (f). The high purity of the microwave signal ( $Nf_m$ ) is possible due to the gain of the OEO feedback loop, which is high enough to oscillate the selected signal.

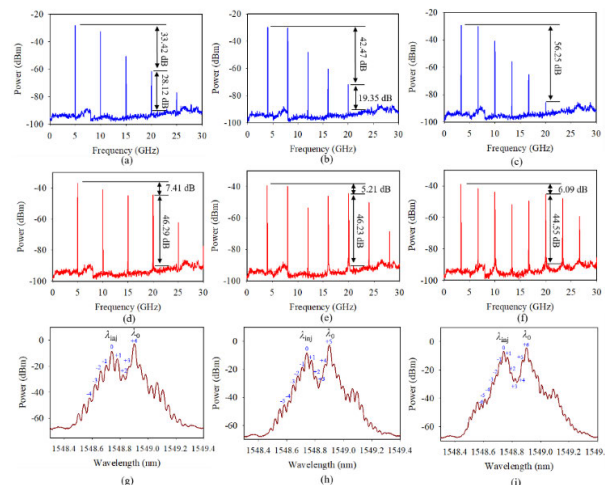
### III. EXPERIMENTAL RESULTS

#### A. OPEN OEO FEEDBACK LOOP

At first, we analyze the open-loop response of the proposed scheme without the modulation of the injected beam (point B is open in Fig.1). The EOM is driven by an electrical signal with a frequency of  $f_m$ , and is injected into the SMFP-LD. We set the wavelength of TL ( $\lambda_{inj}$ ) as 1548.736 nm and the dominant mode of SMFP-LD ( $\lambda_0$ ) as 1548.896 nm, as illustrated in Fig. 3. Figure 3(a) shows the optical spectrum of SMFP-LD with no optical injection under normal biasing conditions. The SMFP-LD has a dominant mode at 1548.896 nm with an SMSR of 34.23 dB under the controlling temperature and driving current of 25.34 °C and 23.2 mA, respectively. Since the external beam injected into the SMFP-LD has a negative wavelength detuning ( $\Delta\lambda = \lambda_0 - \lambda_{inj} = -0.16$  nm), the output optical spectrum of SMFP-LD at point B of Fig. 1 is shown in Fig. 3(b). Figure 3(c) shows the corresponding microwave signal generated by optical beating the injected beam and the dominant mode of the SMFP-LD. The frequency of the generated RF



**FIGURE 3.** The optical spectrum of SMFP-LD with (a) no optical injection, (b) an optical injection, and the electrical spectrum of RF signal generated with (c) optical injection in an SMFP-LD.

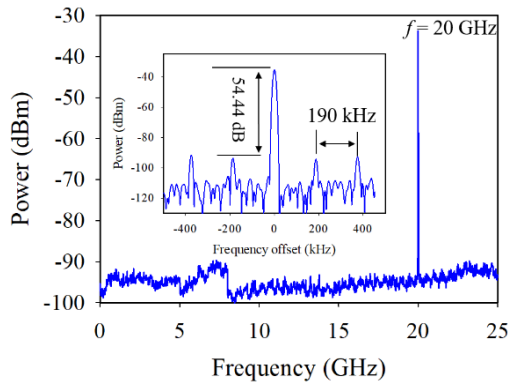


**FIGURE 4.** The electric spectrum of injected beam with the  $f_m = 20/N$ , (a)  $N = 4$ , (b)  $N = 5$ , and (c)  $N = 6$ ; the electric spectrum of (d) 4<sup>th</sup>, (e) 5<sup>th</sup>, and (f) 6<sup>th</sup> harmonics locking to the SMFP-LD, and the corresponding optical spectrum (g), (h) and (i).

signal is 20 GHz with an SNR of 22.93 dB. Even though optical injection to semiconductor laser is a typical, simple, and cost-effective method for generating microwave signal, the inherent unstabilizing factor of the semiconductor laser causes frequency jitter in RF signal. Hence, the microwave signal generated by this method is unstable and has a frequency jitter in a range of about 100 MHz.

Further, the external beam is modulated at the Quadrature Bias point (QB), and the RF signal is generated through the optical beating of the modulated signals. Multiple microwave signals can be generated using this method with modulating frequency,  $f_m = 20/N$  GHz (where 20 GHz is the desired frequency and  $N$  is an integer). Figure 4(a)-(c) shows the electric spectrum results at point A (without injection to SMFP-LD) when  $N = 4, 5$ , and  $6$ , respectively. The generated frequency,  $f = 20$  GHz, with  $N = 4, 5$ , and  $6$ , has an SNR of 28.12 dB, 19.35 dB, and 10.21 dB, and power ratio with the fundamental frequency  $f_m$  as 34.24 dB, 42.47 dB, and 56.25 dB, respectively. Also, we observe that the power of the generated higher frequency RF signal decreases with an increase in harmonics order,  $N$ .

To solve the problem of the high power difference of the RF signal with the fundamental frequency and low SNR, we inject a modulated beam to the SMFP-LD in such a way that one of the harmonics of the modulated beam is locked to the dominant mode of the SMFP-LD. Due to the locking of one of the harmonics into dominant mode and the sufficient gain provided by the SMFP-LD, the power of the RF signal,

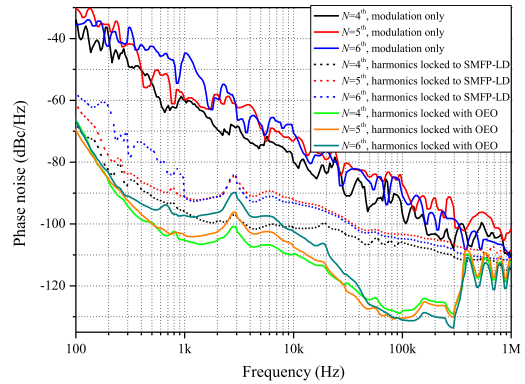


**FIGURE 5.** The electric spectrum of the RF signal with the sextuple frequency generated by the proposed system.

which is multiples of  $f_m$  within the gain bandwidth of the SMFP-LD, is amplified and is further converted to an electric RF signal by optical beating. The electric spectrum of the output of SMFP-LD after harmonics injection locking with  $N = 4, 5,$  and  $6$  are shown in Fig. 4(d)-(f), and their corresponding optical spectrum is shown in Fig. 4(g)-(i), respectively. We observe that with an optical injection to the SMFP-LD, a power gain on the high-order harmonics of the modulated beam results in better SNR of the RF signal at  $f = 20$  GHz with  $N = 4, 5,$  and  $6$  increase and records to 46.29 dB, 46.23 dB, and 44.55 dB, respectively. Hence, with harmonics injection-locked, the SNR of the RF signal at 20 GHz compared to that, with only modulation, is improved by 18.17 dB, 26.88 dB, and 34.34 dB for  $N = 4, 5,$  and  $6,$  respectively. By changing the wavelength of the injected beam and the frequency of the fundamental microwave signal ( $f_m$ ), which match the relation of  $N \cdot f_m = f_0$ , where  $f_0$  is the frequency detuning of the injection beam and the mode of the SMFP-LD slave laser, the RF signal at the output can be flexibly tuned.

**B. CLOSED OEO LOOP**

Though using the harmonics injection locking to the SMFP-LD has improved signal quality in terms of SNR and phase noise, there is still room to improve the RF signal in terms of the signal quality and electric harmonics. We employ an OEO structure to obtain an enhanced high-order selected RF signal. The electric signal generated by PD is fed back to the EOM via an LNF and an EBPF. The electrical gain of the LNF is about 40 dB with a bandwidth of 18 GHz-26.5 GHz, and the center frequency of the EBPF is 20 GHz with a passband bandwidth of 30 MHz. As the gain of the OEO feedback loop is high enough to oscillate the selected signal, it generates a microwave signal of 20 GHz with high spectral purity. The electrical spectrum of the proposed scheme when the OEO is configured to generate a 20 GHz microwave signal is shown in Fig. 5. The obtained signal at  $f = 20$  GHz =  $6f_m$  has an SNR of 54.44 dB, which is 10 dB more than the harmonics injection locking scheme without OEO. In the inset of Fig. 5, we observe the peaks with an



**FIGURE 6.** The phase noise of the generated RF signal (20 GHz) with modulator only, with harmonics locked to the SMFP-LD, and harmonics locked followed by OEO loop for  $N = 4, 5$  and  $6,$  respectively.

interval of 190 kHz, which is due to the length of the OEO loop, which is about 1015 m.

Fig. 6 shows the phase noise of the generated RF signal (20 GHz) with modulator only, with harmonics locked to the SMFP-LD, and with harmonics locked to SMFP-LD followed by OEO loop for different values of  $N$ . The black, red, and blue solid lines show the phase noise of 20 GHz signal generated by using the modulator only with  $N = 4, 5$  and  $6,$  respectively. The recorded phase noises are  $-80.10$  dBc/Hz@10 kHz,  $-73.08$  dBc/Hz@10 kHz, and  $-70.67$  dBc/Hz@10 kHz, for  $N = 4, 5,$  and  $6,$  respectively. The phase noise of the RF signal with harmonically locked SMFP-LD improves by more than  $-20$  dBc/Hz@10kHz compared to that of the modulators only. The phase noise of the 20 GHz signal generated by harmonics locked to SMFP-LD with  $N = 4, 5,$  and  $6$  are shown in the black, red, and blue dotted lines of Fig. 6, respectively, which is recorded as  $-101.37$  dBc/Hz@10kHz,  $-92.22$  dBc/Hz@10kHz, and  $-93.13$  dBc/Hz@10kHz, respectively. The phase noise is further improved by 10 dBc/Hz@10kHz with closed-loop OEO structure and is recorded as  $-109.66$  dBc/Hz@10kHz,  $-107.46$  dBc/Hz@10kHz and  $-102.44$  dBc/Hz@10kHz for  $N = 4, 5$  and  $6,$  respectively. The phase noise for closed OEO for  $N = 4, 5$  and  $6$  are shown with green, orange, and dark cyan lines in Fig. 6, respectively. We can see that irrespective of the order of the harmonics locked to the SMFP-LD, the phase noise is improved with the proposed techniques of harmonics locked OEO structure. The phase noise of 20 GHz at different frequency offset is recorded in Table 1, where the maximum improved phase noise is at the frequency of 100 kHz with the phase noise of  $-131.03$  dBc/Hz@10kHz for  $N = 6.$

Using the proposed technique, a higher multiplication factor can be obtained by locking higher harmonics of the modulating beam to the corresponding mode of the SMFP-LD. However, the gain bandwidth of the SMFP-LD modulation index and bandwidth of the EOM and the PD bandwidth plays a role in limiting the higher multiplication factors. In this work, the multiplication factor is obtained by locking the modulated side mode (harmonics) to either the dominant

**TABLE 1.** The phase noise of the generated RF signal (20 GHz) with modular only, with harmonics locked to the SMFP-LD, and harmonics followed by OEO loop scheme for  $N = 4, 5,$  and  $6$  at 100 Hz, 1 kHz, 10 kHz, 100 kHz, and 1 MHz, respectively.

	Modular Only (dBc/Hz)			Harmonics Locked to the SMFP-LD (dBc/Hz)			Harmonics Locked Followed By OEO Loop (dBc/Hz)		
	4 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>	4 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>	4 <sup>th</sup>	5 <sup>th</sup>	6 <sup>th</sup>
10 Hz	-33.97	-30.32	-35.53	-67.36	-61.11	-57.61	-66.59	-69.64	-66.71
1 kHz	-59.88	-59.78	-44.75	-96.09	-91.20	-91.55	-105.20	-103.76	-97.23
10 kHz	-80.10	-73.08	-70.67	-101.37	-92.22	-93.13	-109.66	-107.46	-102.44
100 kHz	-96.71	-87.21	-90.83	-106.02	-103.36	-104.78	-128.04	-130.51	-131.03
1 MHz	-111.88	-101.37	-111.12	-114.56	-108.72	-110.90	-112.23	-111.27	-113.88

mode or the side mode of the SMFP-LD. Hence, the modulation index and 3dB bandwidth of the EOM play a role in the quality of the output signal in terms of signal-to-noise ratio and the phase noise. Also, on generating an electrical signal at the output, the bandwidth of the PD limits the maximum multiplication factor. On the other hand, when obtaining RF signal with a low order of harmonics, the power of the injected beam should be considered, while making sure that the power of the injected beam and the harmonics do not suppress the dominant mode of the SMFP-LD.

#### IV. CONCLUSION

In this paper, we propose and experimentally demonstrate a frequency multiplier based on harmonics locked in SMFP-LD followed by optoelectronic oscillator. Taking advantage of optical injection with a negative wavelength detuning to the SMFP-LD, we employ the injection of the modulated beam to an SMFP-LD in such a way that the  $N^{\text{th}}$  harmonics of the modulated beam is locked to the dominant mode of the SMFP-LD. The harmonic locked SMFP-LD is further passed through the OEO loop to significantly improve the spectral quality in the SNR and the phase noise. The proposed method outperforms the output signal quality in terms of SNR and phase noise compared with the modulator scheme only and the harmonically locked scheme. A power gain on the selected output RF signal, which is equal to the wavelength detuning between the injected beam and the harmonics-locked corresponding mode in the SMFP-LD ( $N f_m$ ), is obtained through harmonics locked OEO structure. Besides, RF signals with different frequencies, which are the harmonics of the modulating frequency, can be selected by changing the center frequency of EBPF using the same configuration. In the experiment, the wavelength detuning of the injected beam and the mode of the SMFP-LD is 20 GHz. We further analyze the RF signal generation with a different order of harmonics ( $4f_{m1}$ ,  $5f_{m2}$ , and  $6f_{m3} = 20$  GHz) locked to the dominant mode of the SMFP-LD with open and closed OEO loop. The proposed scheme of RF multiplier with closed OEO loop structure outperforms the phase noise of generated RF signal by 20 dBc/Hz @ 10 kHz and 10 dBc/Hz @ 10 kHz to that of using only modulating beam and harmonic locked SMFP-LD (open OEO), respectively. The phase noise of  $-109.66$  dBc/Hz@10 kHz,

$-107.46$  dBc/Hz@10 kHz and  $-102.44$  dBc/Hz@10 kHz is recorded for proposed harmonics-locked OEO with  $N = 4, 5,$  and  $6,$  respectively. The SNR of the sextuple frequency (20 GHz) is 54.44 dB. Hence, our proposed scheme of high spectral purity multiplier, obtained through the harmonics-locked SMFP-LD followed by OEO structure, has the potential for high-frequency applications such as the modern radar for defense, communication system, and the bio-medical.

#### REFERENCES

- [1] J. J. O'Reilly, P. M. Lane, R. Heidemann, and R. Hofstetter, "Optical generation of very narrow linewidth millimeter wave signals," *Electron. Lett.*, vol. 28, no. 25, pp. 2309–2311, 1992.
- [2] G. Qi, J. Yao, J. Seregelyi, S. Paquet, and C. Belisle, "Generation and distribution of a wide-band continuously tunable millimeter-wave signal with an optical external modulation technique," *IEEE Trans. Microw. Theory Techn.*, vol. 53, no. 10, pp. 3090–3097, Oct. 2005.
- [3] R. P. Braun, G. Grosskopf, D. Rohde, and F. Schmidt, "Optical millimeter-wave generation and transmission experiments for mobile 60 GHz band communications," *Electron. Lett.*, vol. 32, no. 7, pp. 626–628, 1996.
- [4] I. F. Akyildiz, J. M. Jornet, and C. Han, "Terahertz band: Next frontier for wireless communications," *Phys. Commun.*, vol. 12, pp. 16–32, Sep. 2014.
- [5] P. Ghelfi, F. Laghezza, F. Scotti, G. Serafino, A. Capria, S. Pinna, D. Onori, C. Porzi, M. Scaffardi, A. Malacarne, V. Vercesi, E. Lazzeri, F. Berizzi, and A. Bogoni, "A fully photonics-based coherent radar system," *Nature*, vol. 507, no. 7492, pp. 341–345, Mar. 2014.
- [6] J. W. Lin, C. L. Lu, H. P. Chuang, F. M. Kuo, J. W. Shi, C. B. Huang, and C. L. Pan, "Photonic generation and detection of W-band chirped millimeter-wave pulses for radar," *IEEE Photon. Technol. Lett.*, vol. 24, no. 16, pp. 1437–1439, Aug. 15, 2012.
- [7] P. H. Siegel, "Terahertz technology in biology and medicine," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 10, pp. 2438–2447, Oct. 2004.
- [8] E.-Q. Chen, X.-D. Lin, G.-Q. Xia, and Z.-M. Wu, "Numerical investigation of the frequency-modulated continuous-wave generation based on an optically injected semiconductor laser with optical feedback stabilization," *Proc. SPIE*, vol. 11545, Oct. 2020, Art. no. 11540B.
- [9] R. Hofstetter, H. Schmuck, and R. Heidemann, "Dispersion effects in optical millimeter-wave systems using self-heterodyne method for transport and generation," *IEEE Trans. Microw. Theory Techn.*, vol. 43, no. 9, pp. 2263–2269, Sep. 1995.
- [10] X. Chen, Z. Deng, and J. Yao, "Photonic generation of microwave signal using a dual-wavelength single-longitudinal-mode fiber ring laser," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 2, pp. 804–809, Feb. 2006.
- [11] M. C. Gross, P. T. Callahan, T. R. Clark, D. Novak, R. B. Waterhouse, and M. L. Dennis, "Tunable millimeter-wave frequency synthesis up to 100 GHz by dual-wavelength Brillouin fiber laser," *Opt. Exp.*, vol. 18, no. 13, pp. 13321–13330, 2010.
- [12] S. Pan and J. Yao, "A wavelength-switchable single-longitudinal-mode dual-wavelength erbium-doped fiber laser for switchable microwave generation," *Opt. Exp.*, vol. 17, no. 7, pp. 5414–5419, Mar. 2009.
- [13] Y. Zhang and S. Pan, "Experimental demonstration of frequency-octupled millimeter-wave signal generation based on a dual-parallel Mach-Zehnder modulator," in *Proc. Microw. Workshop Ser. Millim. Wave Wireless Technol. Appl. (IMWS)*, Sep. 2012, pp. 1–4.

- [14] Y. Gao, A. Wen, Q. Yu, N. Li, G. Lin, S. Xiang, and L. Shang, "Microwave generation with photonic frequency sextupling based on cascaded modulators," *IEEE Photon. Technol. Lett.*, vol. 26, no. 12, pp. 1199–1202, Jun. 15, 2014.
- [15] H. Chi and J. Yao, "Frequency quadrupling and upconversion in a radio over fiber link," *J. Lightw. Technol.*, vol. 26, no. 15, pp. 2706–2711, Aug. 1, 2008.
- [16] P. Bouyer, T. L. Gustavson, K. G. Haritos, and M. A. Kasevich, "Microwave signal generation with optical injection locking," *Opt. Lett.*, vol. 21, no. 18, pp. 1502–1504, 1996.
- [17] A. Hurtado, J. Mee, M. Nami, I. D. Henning, M. J. Adams, and L. F. Lester, "Tunable microwave signal generator with an optically-injected 1310 nm QD-DFB laser," *Opt. Exp.*, vol. 21, no. 9, pp. 10772–10778, 2013.
- [18] R. T. Ramos and A. J. Seeds, "Fast heterodyne optical phase-lock loop using double quantum well laser diodes," *Electron. Lett.*, vol. 28, no. 1, pp. 82–83, Jan. 1992.
- [19] F. Z. Fan and M. Dagenais, "Optical generation of a megahertz-linewidth microwave signal using semiconductor lasers and a discriminator-aided phase-locked loop," *IEEE Trans. Microw. Theory Techn.*, vol. 45, no. 8, pp. 1296–1300, Aug. 1997.
- [20] J.-P. Zhuang and S.-C. Chan, "Tunable photonic microwave generation using optically injected semiconductor laser dynamics with optical feedback stabilization," *Opt. Lett.*, vol. 38, no. 3, pp. 344–346, 2013.
- [21] K.-H. Lo, S.-K. Hwang, and S. Donati, "Optical feedback stabilization of photonic microwave generation using period-one nonlinear dynamics of semiconductor lasers," *Opt. Exp.*, vol. 22, no. 15, pp. 18648–18661, 2014.
- [22] X. S. Yao and L. Maleki, "Optoelectronic microwave oscillator," *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 13, no. 8, pp. 1725–1735, 1996.
- [23] L. C. Lin, S. H. Liu, and F. Y. Lin, "Stability of period-one (P1) oscillations generated by semiconductor lasers subject to optical injection or optical feedback," *Opt. Exp.*, vol. 25, no. 21, pp. 25523–25532, 2017.
- [24] S. Liu, K. Lv, J. Fu, L. Wu, W. Pan, and S. Pan, "Wideband microwave frequency division based on an optoelectronic oscillator," *IEEE Photon. Technol. Lett.*, vol. 31, no. 5, pp. 389–392, Mar. 1, 2019.
- [25] Y. Zhang and S. Pan, "Experimental demonstration of frequency-octupled millimeter-wave signal generation based on a dual-parallel Mach-Zehnder modulator," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Sep. 2012, pp. 1–4.
- [26] W. Li and J. Yao, "Investigation of photonic assisted microwave frequency multiplication based on external modulation," *IEEE Trans. Microw. Theory Techn.*, vol. 58, no. 11, pp. 3259–3268, Nov. 2010.
- [27] Y. D. Jeong, Y. H. Won, S. O. Choi, and J. H. Yoon, "Tunable single-mode Fabry-Pérot laser diode using a built-in external cavity and its modulation characteristics," *Opt. Lett.*, vol. 31, no. 17, p. 2586, Sep. 2006.



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