Stable multi-frequency generator based on phase-locked optical frequency combs

Chao Zhang (张 超), Dongning Sun (孙东宁), Weilin Xie (谢玮霖), Zongyang Xia (夏宗杨), Siwei Wang (王锶惟), Hongxiao Shi (石宏霄), Yitian Tong (佟亦天), Yi Dong (董毅)*, and Weisheng Hu (胡卫生)

State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, Shanghai 200240, China

**Corresponding author: yidong@sjtu.edu.cn*

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A photonic generation of multi-frequency source based on the heterodyne of two phase-locked optical frequency combs (OFCs) is proposed and demonstrated. By applying an optical phase-locked loop, the phase noise induced by optical links is decreased by approximately 70, 66, and 35 dB at 0.01, 0.1, and 1.0 Hz offset frequencies, respectively. The proposed scheme provides 8 radio frequency signals, the frequencies of which span from 540 to 4040 MHz, with a 500-MHz interval. The number of generated signals can be readily scaled by using OFCs with broader bands, whereas the frequencies can be scaled by tuning the repetition rates of OFCs.

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Future military radio frequency (RF) systems are increasingly being driven toward high frequencies and large bandwidths by user requirements[1]. Channelized receivers are being developed with channel bandwidths restricted by state-of-the-art electronic analog-to-digital converters to monitor the entire frequency range. In wideband channelized receivers[2], multiple local oscillator (LO) signals are simultaneously required to shift the desired signals in different frequency bands to a common intermediate frequency band. In general, these signals are provided either by numerous different frequency synthesizers, each of which is synchronized to the same reference clock, or by a single multi-output frequency synthesizer that integrates several phase-locked loops (PLLs) and voltage-controlled oscillators (VCOs)[3,4]. The drawback is that the number of employed VCOs or PLL circuits is proportional to the quantity of desired LOs. Consequently, these systems become complex and exhibit high-power consumption.

Nowadays, several schemes for the photonic generation of microwave signals have been proposed because of the broad bandwidth and low loss offered by modern photonics[5−9]. Coddington *et al*. proposed to generate multi-frequency RF signals by beating two optical frequency combs (OFCs) with different repetition rates[7]. However, the produced signal suffers from phase fluctuation induced by optical links because OFCs travel through separate fiber links before they beat[8].

In this letter, we propose a photonic approach to generate multi-frequency RF signals simultaneously based on the heterodyne of two phase-locked OFCs. By applying an optical PLL (OPLL), the phase noise induced by optical links is decreased by approximately 70, 66, and 35 dB at 0.01, 0.1, and 1.0 Hz offset frequencies, respectively. The proposed scheme provides 8 RF signals, the frequencies of which span from 540 to 4040 MHz, with a 500-MHz interval.

The proposed scheme is shown in Fig. 1. The continuous-wave (CW) lightwave from a narrow-linewidth laser is split equally by an optical coupler (OC1). On one path, OFC1 is obtained by directly modulating the CW lightwave with a waveguide Fabry-Perot electro-optic modulator (FP-EOM), which is driven by RF1 that is generated from PLL1. RF1 can be expressed as cos $(2\pi f_1 t + \varphi_2)$, where f_1 and φ_1 represent the frequency and initial phase of RF1, respectively.

On the other path, OFC2 is obtained by modulating the CW lightwave with a cascaded intensity modulator (IM) and a phase modulator (PM)[10−13], which is driven by RF2 that is generated from PLL2. RF2 is expressed as $\cos(2\pi f_2 t + \varphi_2)$, where f_2 and φ_2 represent the frequency and initial phase of RF2, respectively. Then, the frequency of OFC2 is upshifted by f_{A0} with an acousto-optic frequency shifter (AOFS), which is driven by PLL3. All PLL circuits share the same reference signal[Ref]. Auto bias control can be used to maintain the modulators in optimal bias[14].

As illustrated in Fig. 2, the outputs of the arms are two OFCs that exhibit center frequencies biased by f_{A0} and different spacing of f_1 and f_2. OFCs travel through

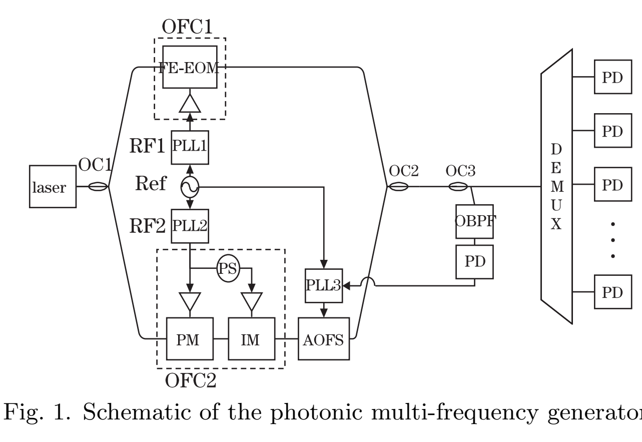

Fig. 1. Schematic of the photonic multi-frequency generator.

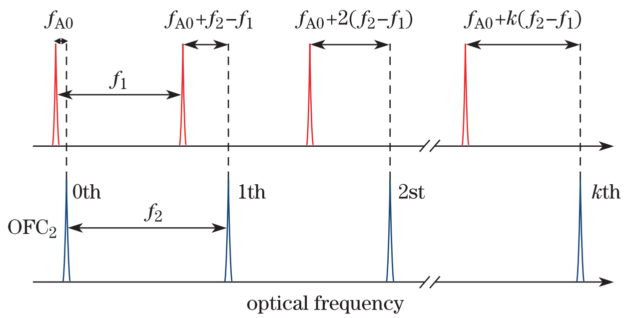

Fig. 2. Demonstration of OFCs with different spacing and a bias in center frequency.

two separated loose fibers, and the effective lengths of the optical links fluctuate because of changes in environmental temperature and mechanical stress. Hence, the outputs of the arms suffer from phase noise induced by fiber links, which can be expressed as

$$E_{\mathrm{OFC1}}(t) = \sum_{k=M2}^{M_1} a_k \exp\{\mathrm{i}[2\pi(f_\mathrm{c} + kf_1)t + k\varphi_1]\}, \quad (1)$$

$$E_{\mathrm{OFC2_A}}(t) = \sum_{k=N2}^{N_1} b_k \exp\{\mathrm{i}[2\pi(f_\mathrm{c} + f_{\mathrm{A0}} + kf_2)(t-\tau) + k\varphi_2 + \psi_\mathrm{A}]\}, \quad (2)$$

where a_k and b_k are the complex amplitudes of the kth order optical carrier of the OFCs, f_c is the center frequency of the CW lightwave, φ_A is the phase induced by the AOFS, and τ represents the fluctuation of the difference between the transmission delays of the OFCs.

Combined by an OC2 and demultiplexed by a DEMUX channel spacing of f_1, multi-frequency RF signals can be generated by beating the k_{th} order optical carriers of the OFCs in the photodetector (PD) and can be expressed as

$$E_\mathrm{k}(t) = K|a_k b_k| \cos\{2\pi[k(f_2 - f_1) + f_{\mathrm{A0}}]\, t + \varphi_{1k} + k(\varphi_2 - \varphi_1) + \varphi_\mathrm{A}\}, \quad (3)$$

$$\varphi_{1k} = -2\pi(f_\mathrm{c} + f_{\mathrm{A0}})\tau + 2\pi k f_2 \tau, \quad (4)$$

where K is a constant determined by the system parameters. As shown in Eq. (3), the power of the specific RF signal is proportional to the product of those of the corresponding beating carriers. In addition, the generated signal suffers from the phase noise induced by optical links denoted as φ_{1k}. As signal amplitude has a limited effect on analyzing the system, it is omitted in the following simplified equations. Thus, the signal can be rewritten as

$$E_\mathrm{k}(t) = \cos\{2\pi[k(f_2 - f_1) + f_{\mathrm{A0}}]\, t + \varphi_{1k} + k(\varphi_2 - \varphi_1) + \varphi_\mathrm{A}\}. \quad (5)$$

To compensate for the phase fluctuation φ_{1k}, an OC3 is used to split a portion of the combined light for feedback. The 0^{th} order optical carriers of the feedback OFCs are filtered by using an optical band-pass filter (OBPF) and detected by a low-frequency PD. The detected signal can be expressed as

$$E_\mathrm{f}(t) = \cos(2\pi f_{\mathrm{A0}} t + \varphi_f + \varphi_\mathrm{A}), \quad (6)$$

$$\varphi_\mathrm{f} = -2\pi(f_c + f_{\mathrm{A0}})\tau, \quad (7)$$

where φ_f represents the link-induced phase fluctuation of the detected signal. The signal is then sent to PLL3, which compares the phase of the signal with that of the reference and compensates for the phase error by controlling the frequency of the driving signal of AOFS. When PLL is locked, the equation is presented as

$$\varphi_\mathrm{f} + \varphi_\mathrm{A} = \mathrm{const}. \quad (8)$$

Thus, the multi-frequency RF signals can be rewritten as

$$E_\mathrm{k}(t) = \cos\{2\pi[k(f_2 - f_1) + f_{\mathrm{A0}}]t + 2\pi k f_2 \tau + k(\varphi_2 - \varphi_1) + \mathrm{const}\}, \quad (9)$$

where $2\pi k f_2 \tau$ is the residual phase fluctuation that is induced by optical links. Notably, the decrease in link-induced phase noise can be expressed as

$$-20\log\left(\left|\frac{2\pi k f_2 \tau}{\varphi_\mathrm{f}}\right|\right) \approx -20\log\left(\frac{kf_2}{f_\mathrm{c}}\right). \quad (10)$$

Assuming $f_2 = 25.5$ GHz and $f_\mathrm{c} \approx 193$ THz, which is consistent with the experiment conditions, the phase noise induced by optical links can be decreased by $77.6 - 20\log(k)$ dB theoretically. Therefore, the proposed scheme effectively compensates the phase noise induced by optical links.

A proof-of-concept experiment was performed based on the scheme in Fig. 1. A laser operating at 1550 nm with less than 10-kHz linewidth was used as the optical source. The FP-EOM (WR-250-03) with 2.5-GHz free spectral range was driven by RF1 at 25 GHz. The generated OFC1, shown in Fig. 3(a), has a 25-GHz frequency interval and more than 2-THz spectral span. In the other path, the cascaded PM and IM were driven by RF2 at

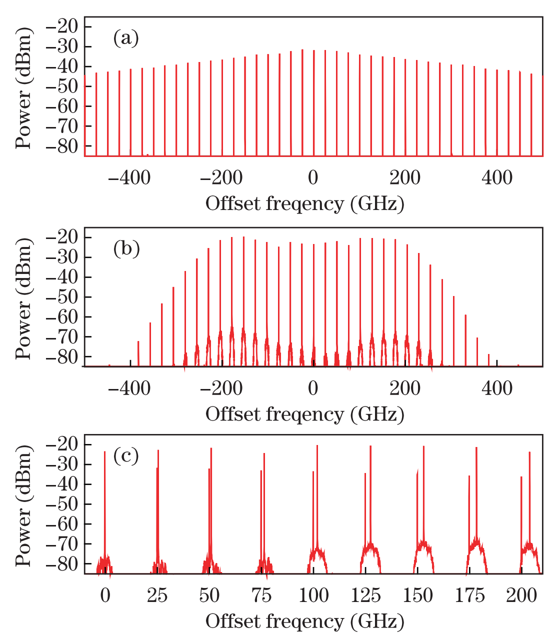

Fig. 3. Optical spectra of (a) OFC1, (b) OFC2, and (c) combined OFCs.

25.5 GHz. As shown in Fig. 3(b), the generated OFC2 had 17 optical carriers within a 3-dB power variation. The AOFS frequency upshifts the entire OFC2 by 40 MHz. The OFCs are combined by a polarization-maintaining coupler, as shown in Fig. 3(c).

A tunable filter with a minimum bandwidth of approximately 0.2 nm was employed instead of the optical DEMUX to filter the different carriers of the combined OFCs. The proposed scheme generates 8 RF signals, the frequencies of which span from 540 to 4040 MHz, with a 500-MHz interval. The number of generated signals can be readily scaled by using OFCs with broader bands, whereas the frequencies can be scaled by tuning the repetition rates of the OFCs[13,15,16]. Figure 4 presents the spectrum of the obtained signal at 4.04 GHz over a 20-MHz span, with a resolution bandwidth of 10 kHz. The signal trace has a narrow line and a carrier-to-noise ratio above 50 dB.

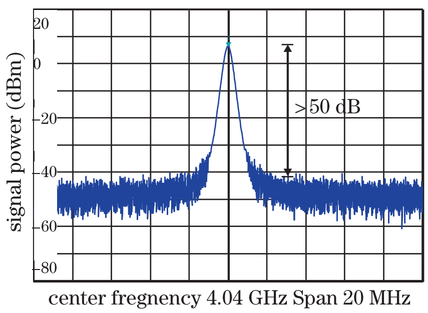

Fig. 4. Measured frequency spectra of LOs at 4.04 GHz.

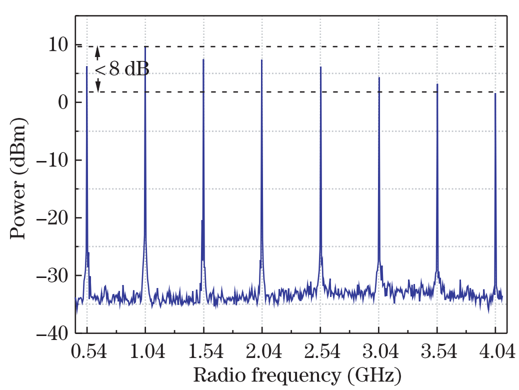

Fig. 5. Measured frequency spectrum of the RF signal with different frequencies.

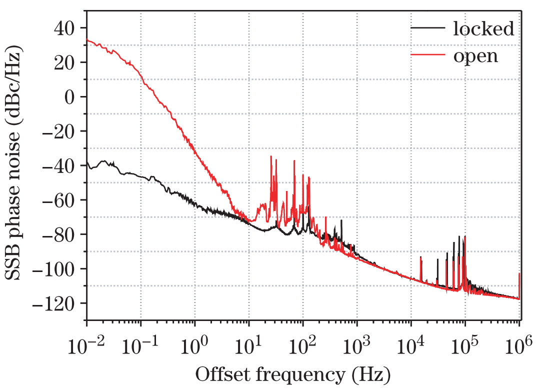

Fig. 6. Comparison of phase noises of the 40-MHz feedback signal under open and locked cases.

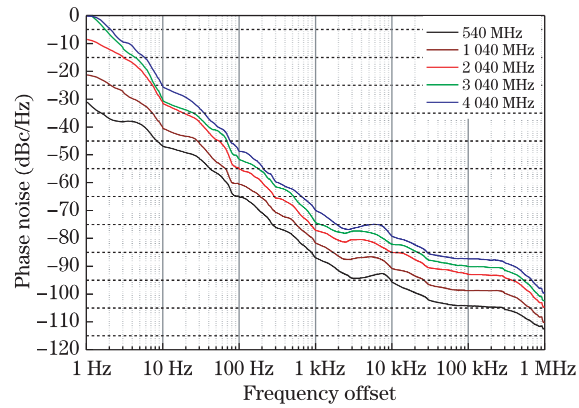

Fig. 7. Comparison of phase noises of different LOs.

The first to eighth order carriers of the combined OFCs were filtered and detected to compare the power of different RF signals. As shown in Fig. 5, the signals at various frequencies have different powers with the deviation of 8 dB. This result is attributed to the fact that the OFCs are not flat in the experiment. The result can be improved by using flatter OFCs[17].

The phase noises of the 40 MHz feedback signal under locked and open conditions are compared to verify the performance of the OPLL. The results are shown in Fig. 6. RF1 and RF2 have no effect on the 40 MHz signal according to Eqs. (6) and (7). Thus, the phase noise is mainly attributed to optical links. When the OPLL is unlocked, the phase noise reaches over 35, 10, and –30 dBc/Hz at 0.01, 0.1, and 1.0 Hz offset frequencies, respectively. When the loop is locked, the phase noise decreases by approximately 70, 66, and 35 dB at 0.01, 0.1, and 1.0 Hz offset frequencies, respectively. For offset frequencies above 100 Hz, the signals exhibit virtually the same phase noise. This result is attributed to the fact that fiber links mainly induce low-frequency phase noises[8].

The measured phase noises of the generated 540, 1040, 2040, 3040, and 4040 MHz signals are shown in Fig. 7. The phase noise performance of the signals degrades as frequency increases. The degrading trend is believed to be mainly caused by the term $k(\varphi_2 - \varphi_1) + 2\pi k f_2 \tau$. Thus, the performance of the obtained multi-frequency RF signals can be improved by using RF1 and RF2 with improved qualities. Further work can be focused on compensating the term τ by using a piezoelectric fiber stretcher[18].

In conclusion, an approach to generate multi-frequency RF signals based on the heterodyne of two phase-locked OFCs is proposed and experimentally demonstrated. By applying an OPLL, phase noise induced by optical links decreases by approximately $77.6 - 20\log(k)$ dB theoretically. The proposed scheme provides 8 RF signals, the frequencies of which span from 540 to 4040 MHz, with a 500-MHz interval. The number of generated signals can be readily scaled by using OFCs with broader bands, whereas the frequencies can be scaled by tuning the repetition rates of OFCs. The scheme is particularly suitable for applications in wideband channelized receivers that require good extensibility and flexibility.

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