Phase noise measurement of wideband microwave sources based on a microwave photonic frequency down-converter

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An approach for phase noise measurement of microwave signal sources based on a microwave photonic frequency down-converter is proposed. Using the same optical carrier, the microwave signal under test is applied to generate two +1st-order optical sidebands by two stages of electro-optical modulations. A time delay is introduced between the two sidebands through a span of fiber. By beating the two +1st-order sidebands at a photodetector, frequency down-conversion is implemented, and phase noise of the signal under test can be calculated thereafter. The system has a very large operation bandwidth thanks to the frequency conversion in the optical domain, and good phase noise measurement sensitivity can be achieved since the signal degradation caused by electrical amplifiers is avoided. An experiment is carried out. The phase noise measured by the proposed system agrees well with that measured by a commercial spectrum analyzer or provided by the datasheet. A large operation bandwidth of 5–40 GHz is demonstrated using the proposed system. Moreover, good phase noise floor is achieved (−123 dBc/Hz at 1 kHz and −137 dBc/Hz at 10 kHz at 10 GHz), which is nearly constant over the full measurement range.

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The development of ultra-low phase noise oscillators, especially the optoelectronic oscillators (OEOs) that can generate a 10-GHz signal with a phase noise as low as −163 dBc/Hz at 6-kHz offset [1,2], has stimulated great interest to realize precise phase noise measurement of microwave-signal sources. One typical method for phase noise measurement is implemented based on heterodyning, i.e., the signal under test is mixed with a reference source having the same frequency, by which the obtained low-frequency components are proportional to the phase noise of the signal under test [3,4]. However, the reference source should have a phase noise much lower than the signal under test to guarantee the accurate measurement. To avoid the use of an ultra-low-phase-noise and widely tunable reference signal, a delay-line-based method is proposed [5,6]. In this method, the signal under test is split into two branches, one of which is delayed by a certain time and then mixed with the signal in the other branch. Since a larger time delay leads to a higher sensitivity of the phase noise measurement, optical fiber is usually chosen to provide the long time delay with negligible loss and very high reliability. The main problem with such phase noise measurement systems is that the operation bandwidth is usually limited by the electrical devices such as the electrical amplifiers and mixers. Recently, a wideband phase noise measurement scheme using a multifunctional microwave photonic processor was proposed, in which the microwave photonic processor realizes the functions of electrical-to-optical conversion, time delaying, and phase shifting of the delayed signal [7]. However, the frequency mixing is performed in the electrical domain, which still restricts the operational bandwidth. Another problem with both the heterodyning method and the delay-line method is that electrical amplifiers are usually needed to ensure a satisfactory signal power level before electrical mixing. The signal distortion in the amplification stage will reduce the measuring sensitivity of the system, especially when the signal under test has a high frequency.

In this Letter, we propose and demonstrate a delay-line-based phase noise measurement scheme utilizing a microwave photonic frequency down-converter. In the proposed system, the electrical-to-optical conversion, the time delay, and the frequency mixing are all implemented by the microwave photonic-frequency down-converter. Microwave photonic-frequency mixing has been demonstrated to have very wide bandwidth [8,9], thus a large operational bandwidth can be achieved using the proposed system. In addition, the sensitivity degradation due to electrical signal amplification is avoided since no electrical amplifier is required in the proposed system.

Figure 1 shows the schematic diagram of the proposed phase noise measurement system. It consists of a laser diode (LD), two electro-optic modulators (EOMs), a span of optical fiber, a microwave power divider, a microwave

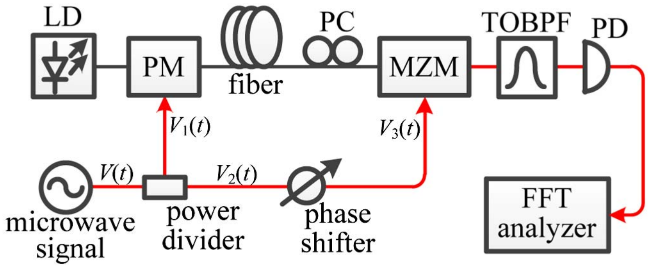

Fig. 1. Schematic diagram of the proposed phase noise measurement system. PC, polarization controller.

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phase shifter, a tunable optical band pass filter (TOBPF), and a photodetector (PD). Each EOM is used to generate two first-order optical sidebands, and it can be either a phase modulator (PM) or a Mach–Zehnder modulator (MZM). The use of two PMs would be the best considering the low insertion loss and the bias-drifting-free property of PMs. However, based on the available devices in the experiment, we only consider to apply a PM and an MZM.

Mathematically, the signal under test can be written as

$$V(t) = V_0 \cos[\omega t + \varphi(t)], \tag{1}$$

where V_0 is the amplitude, ω is the angular frequency, and $\varphi(t)$ is the phase fluctuations. Because the amplitude noise of a microwave signal source can be substantially reduced by a limiter, V_0 can be seen as a constant. In Fig. 1, $V(t)$ is divided into two branches by a power divider and the obtained two signals are $V_1(t) = V_1 \cos[\omega t + \varphi(t)]$ and $V_2(t) = V_2 \cos[\omega t + \varphi(t)]$, respectively. By introducing a tunable phase shift of θ to $V_2(t)$ using a phase shifter, the signal takes the form of $V_3(t) = V_3 \cos[\omega t + \varphi(t) + \theta]$.

Assuming the optical field of the continuous wave (CW) light from the LD is $E_c \exp(j\omega_c t)$, where E_c is the amplitude and ω_c is the angular frequency, after phase modulation at the PM driven by $V_1(t)$, the optical signal is given by

$$E_{o1}(t) = E_c \exp j\left[\omega_c t + \frac{\pi V_1(t)}{V_{\pi 1}}\right], \tag{2}$$

where $V_{\pi 1}$ is the half-wave voltage of the PM. Then, a time delay of τ is introduced by the optical fiber, and the optical signal becomes

$$E_{o2}(t) = E_c \exp j\left[\omega_c(t-\tau) + \frac{\pi V_1(t-\tau)}{V_{\pi 1}}\right]. \tag{3}$$

After that, the delayed optical signal is modulated at the MZM driven by $V_3(t)$ and the output optical signal is

$$E_{o3}(t) = E_c \cos\frac{\pi(V_3(t) - V_B)}{2V_{\pi 2}} \times \exp j\left[\omega_c(t-\tau) + \frac{\pi V_1(t-\tau)}{V_{\pi 1}} + \frac{\pi(V_3(t) + V_B)}{2V_{\pi 2}}\right], \tag{4}$$

where $V_{\pi 2}$ is the half-wave voltage, and V_B is the bias voltage of the MZM. After the two stages of modulations by the PM and the MZM, two +1st-order sidebands and two −1st-order sidebands are generated. Following the MZM, a TOBPF is applied to select out the two +1st-order sidebands. Based on the Jacobi–Anger expansions and ignoring the higher order sidebands during calculation, the optical signal after the TOBPF can be expressed as

$$E_o(t) \propto E_c(Ae^{j[\varphi(t-\tau)-\omega\tau]} + Be^{j[\varphi(t)+\theta]})e^{j\left[(\omega_c+\omega)t-\omega_c\tau+\frac{\beta_B}{2}\right]}, \tag{5}$$

where $A = J_1(\beta_1)[-2J_1^2(\beta_2/2)\sin(\beta_B/2) + jJ_0^2(\beta_2/2)\cos(\beta_B/2)]$, $B = J_0(\beta_1)J_0(\beta_2/2)J_1(\beta_2/2)[\sin(\beta_B) + j\cos(\beta_B)]$, $\beta_1 = \pi V_1/V_{\pi 1}$, $\beta_2 = \pi V_3/V_{\pi 2}$, $\beta_B = \pi V_B/V_{\pi 2}$, and J_m is the mth order Bessel function of the first kind. Then, this signal is sent to a PD for square-law detection. To achieve a high heterodyning efficiency at the PD, the selected two sidebands should have similar powers, which can be achieved by tuning the bias voltage of the MZM. After tuning the electrical phase shifter to let $\theta + \omega\tau + \phi = \pi/2$, where $\phi = \arctan(C/D)$ with $C = [J_0^2(\beta_2/2)/2 + J_1^2(\beta_2/2)]\sin(\beta_B)$ and $D = [J_0^2(\beta_2/2)\cos^2(\beta_B/2) - 2J_1^2(\beta_2/2)\sin^2(\beta_B/2)]$, the output current from the PD is

$$I_o(t) \propto E \sin[\varphi(t) - \varphi(t-\tau)] \approx E[\varphi(t) - \varphi(t-\tau)], \tag{6}$$

where $E = 2E_c^2\sqrt{C^2 + D^2}$. Based on (6), the power spectral density of $I_o(t)$ can be written as [4]

$$S_o(f) \propto 4E^2 \sin^2(\pi f\tau) S_\varphi(f), \tag{7}$$

where $S_\phi(f)$ is the spectral density of the phase fluctuations. If $S_o(f)$ is measured by a fast Fourier transform (FFT) analyzer, the single-sideband phase noise spectral density can be calculated by

$$L(f) = \frac{S_\varphi(f)}{2} \propto \frac{S_o(f)}{8E^2\sin^2(\pi f\tau)}. \tag{8}$$

The proposed system can be treated as a microwave photonic-frequency down-converter realized by beating the two +1st-order sidebands at the PD, and the two sidebands are time delayed between each other. Considering the two optical sidebands have very close frequencies, a low-speed PD can be chosen with possibly higher sensitivity, and thus a lower phase noise measuring floor can be achieved. Electrical mixing and amplification are not required in the proposed system. Therefore, the bandwidth limitation due to the electrical mixers and sensitivity degradation caused by electrical amplifiers can be avoided. It should be noted that a wideband RF phase shifter is still needed in the proposed system to ensure the large operation bandwidth, which might also be implemented based on microwave photonic techniques.

To investigate the performance of the proposed system, an experiment is carried out based on the setup shown in Fig. 1. In the experiment, the CW light is generated by a narrow linewidth LD (TeraXion. Inc.) with a wavelength of 1550 nm and an optical power of 19 dBm. Both the PM (EOSPACE Inc.) and the MZM (Fujitsu Inc.) have a bandwidth of 40 GHz, and the half-wave voltages are ~4 V and ~3.5 V, respectively. The total insertion loss of the two modulators is about 10 dB. The fiber delay line is a span of 2-km single-mode fiber (SMF). A TOBPF (Yenista XTM-50) with an edge slope of more than 500 dB/nm is applied to select the +1st-order sidebands. Then, the obtained optical signal is sent to a PD with a responsivity of 0.85 A/W and a sensitivity of −19 dBm at 10 Gb/s. The obtained electrical signal is analyzed by an FFT analyzer. Based on (8), the phase noise can be calculated.

To check the accuracy of the proposed phase noise measurement system, the phase noise of a 10-GHz clock

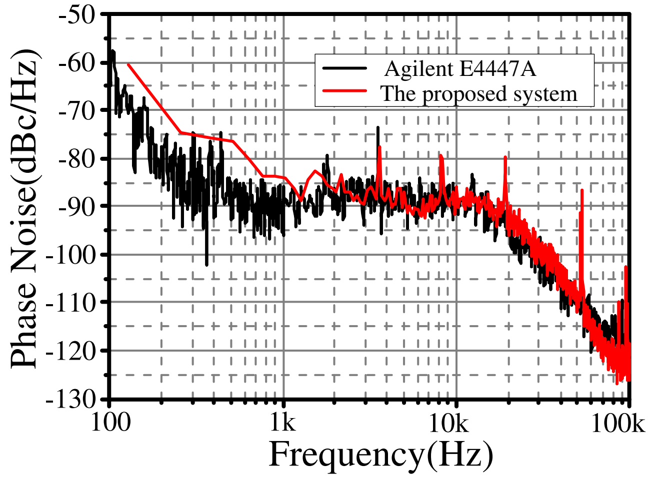

Fig. 2. Phase noise of a 10-GHz clock signal measured by the proposed system (red curve), and that measured by a commercial spectrum analyzer (black curve).

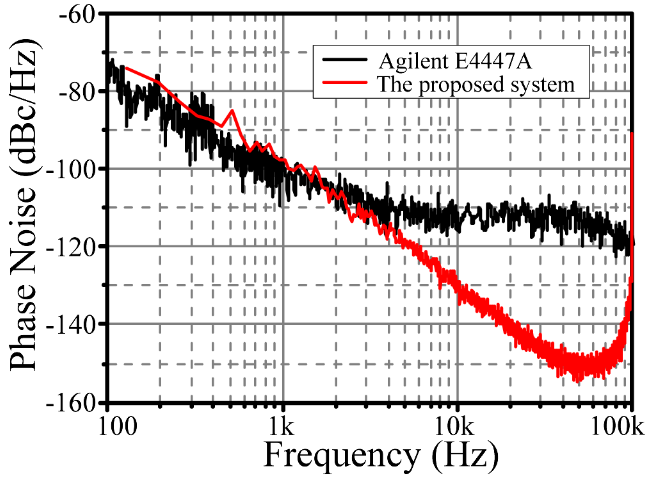

Fig. 4. Phase noise of a 10-GHz OEO measured by the proposed system (red curve), and that measured by the commercial spectrum analyzer Agilent-E4447 (black curve).

signal generated from a pulse pattern generator (Anritsu MP1763C) is tested, with the result shown in Fig. 2. As a comparison, the phase noise measured by a commercial spectrum analyzer (Agilent-E4447) is also included in Fig. 2. It can be seen that the two curves in Fig. 2 are very close to each other especially for the frequency offset over 1 kHz, indicating that the result measured by the proposed system is reliable. For frequency offset less than 1 kHz, there is a slight difference, which is mainly due to the flicker noise in the PD. By using a PD with better noise performance, the difference can be minimized. The phase noise floor of the proposed system for measuring a 10-GHz microwave signal source is tested according to the method in [7]. The result is shown in Fig. 3. As can be seen, the noise floor at 1 kHz and at 10 kHz offset is −123 dBc/Hz and −137 dBc/Hz, respectively, which means good sensitivity is achieved by the proposed method. To further confirm the good sensitivity of the proposed system, the phase noise of a 10-GHz OEO is measured. The OEO has a dual-loop structure with 1- and 0.6-km fiber in each loop, which has been proved to have a very low phase noise [10]. Figure 4 shows the results measured by the proposed system and by Agilent-E4447, respectively. Obviously, an incorrect result is obtained by using Agilent-E4447 since the phase noise of the OEO is better than the phase noise floor of the spectrum analyzer (about −110 dBc/Hzat 10 kHz at 10 GHz). Precise phase noise of the OEO is obtained (−132 dBc/Hz at 10-kHz offset) by the proposed phase noise measurement system.

One of the advantages of the proposed system is the large operation bandwidth. To verify this property, the phase noise of a broadband microwave signal source (Agilent 8257D) is tested by the proposed system. Figure 5 shows the measured phase noise at 10-kHz offset when the frequency of the signal source changes from 5 to 40 GHz. In Fig. 5, the typical values of the phase noise provided by the datasheet of the signal generator are also included. It can be found that the differences between the measured results and the typical values are below 4 dB. This not only confirms the accuracy of the proposed method again, but also proves that the proposed system

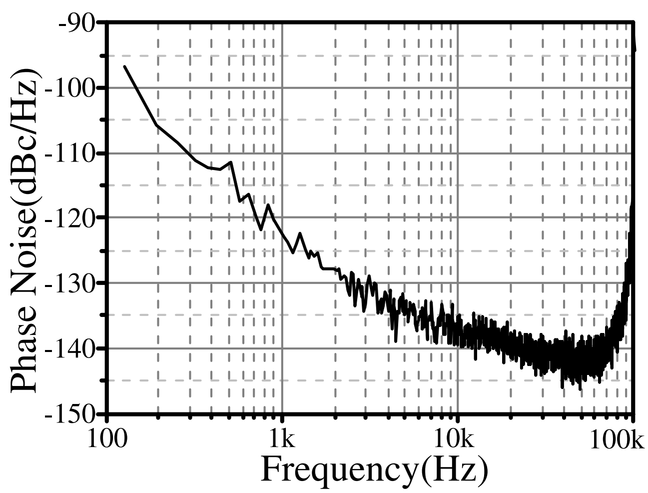

Fig. 3. Phase noise floor of the proposed system at 10 GHz.

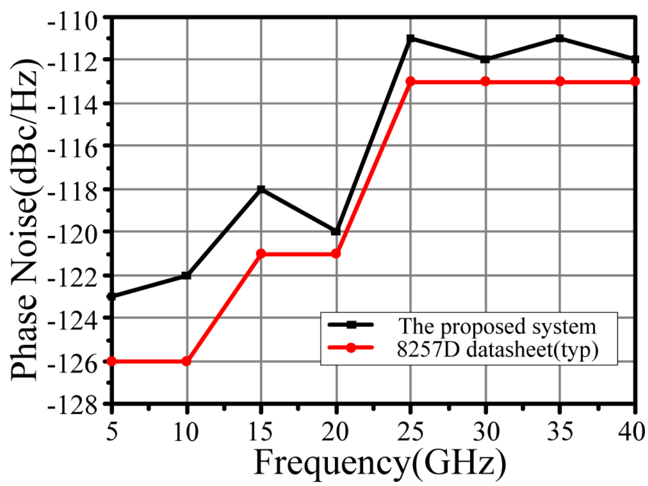

Fig. 5. Phase noises of the wideband signal source (Agilent 8257D) measured by the proposed system and provided by the datasheet (typical value).

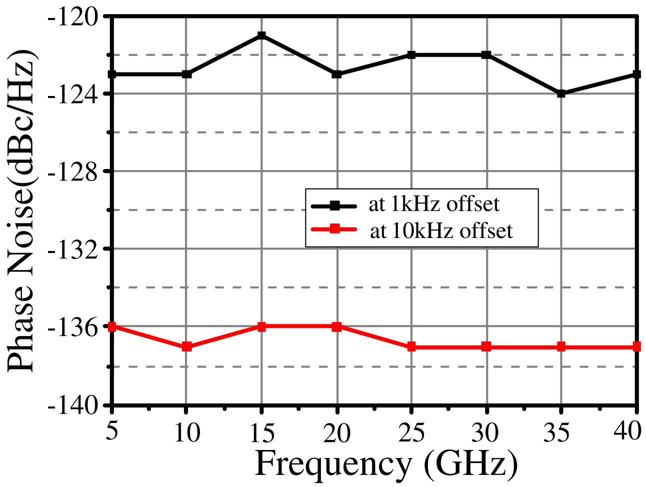

Fig. 6. Phase noise floor at 1- and 10-kHz offset in the frequency range from 5 to 40 GHz.

can operate at a large frequency range from 5 to 40 GHz. Here, the lower limit of the frequency range is determined by the TOBPF edge slope, which should be sharp enough to separate the +1st-order sidebands from the optical carrier, while the upper limit of the measurement frequency rage is determined by the bandwidth of the PM and the MZM. The phase noise floors when the frequency of the signal under test changes from 5 to 40 GHz are also studied. Figure 6 shows the phase noise floor at 1-kHz and at 10-kHz offset, respectively, as the signal frequency changes. In Fig. 6, the fluctuations of the phase noise floor at 1- and at 10-kHz offset are kept within 3 dB and 1 dB, respectively, which means the proposed system has near constant sensitivity over the full measurement range.

In conclusion, a novel approach to measuring the phase noise of wideband microwave sources has been proposed and experimentally demonstrated based on a microwave photonic frequency down-converter. In the experiment, the phase noise of a 10-GHz clock signal is measured accurately and the phase noise floor reaches −123 dBc/Hz at 1 kHz and −137 dBc/Hz at 10 kHz, respectively. Although the phase noise floor of the proposed system is similar with other works based on the photonic delay-line technique [4–6], the previous works are focused on the measurement of a single-frequency source. It is easy for the proposed scheme to measure the phase noise of signal sources in a large frequency range. In the experiment, the large operation bandwidth of the proposed system is demonstrated in the frequency range from 5 to 40 GHz, and a nearly frequency-independent phase noise floor is achieved.

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