Wideband Phase Noise Measurement Using a Multifunctional Microwave Photonic Processor

Dengjian Zhu, Fangzheng Zhang, Pei Zhou, Dan Zhu, and Shilong Pan, *Senior Member, IEEE*

***Abstract*— A novel scheme for measuring the phase noise of microwave signal sources is proposed based on the delay-line method using a multifunctional microwave photonic processor, which can simultaneously implement the electrical-to-optical conversion, provide a time delay, and control the phase of the output microwave signal. Thanks to the microwave photonic processor, the requirement for accurate phase control is relaxed and a large operation bandwidth of the phase noise measurement system can be achieved. An experiment is performed. The phase noise measured by the proposed system agrees well with the result measured by a commercial spectrum analyzer, and the noise floor of the measuring system is lower than −130 dBc/Hz at 10 kHz frequency offset. The large operation bandwidth is also verified by measuring the phase noise of a wideband signal source in a frequency range from 5 to 40 GHz without rebuilding the system.**

***Index Terms*— Microwave photonics, phase noise measurement, photonic-delay method.**

I. INTRODUCTION

MICROWAVE source is one of the key devices in modern radar, communication and measurement systems. In these systems, a low phase noise microwave signal source is always preferred to achieve better performance. Therefore, ultra-low phase noise oscillators have been developing rapidly, especially for the optoelectronic oscillators (OEO) which can achieve a high-purity 10-GHz signal with a phase noise as low as −163 dBc/Hz@6 kHz offset [1]–[3]. However, it is extremely challenging to precisely measure such low phase noise in such high frequency band. In the current stage, the most widely used method for phase noise measurement is based on heterodyning, i.e., the signal under test is mixed with a reference source at a mixer. The obtained low frequency components is proportional to the phase fluctuations of the signal under test, and the phase noise can be calculated thereafter [2], [4]–[7]. However, the measuring accuracy and operation bandwidth of such systems are limited by the reference source. If the signal under test has an ultra-low phase noise below the noise floor of the measurement system, the measured results are unreliable. To solve this problem, the delay-line method is proposed for phase noise measurement, using a delayed copy of the original signal as the reference source [6], [7]. To achieve better de-correlation between the two branches, usually, a long time delay is required. Thanks to the low loss, large bandwidth and small signal distortion, optical fiber is the optimal device to provide long time delays [5], [8]–[12]. In the conventional fiber delay-line based phase-noise measurement systems, a continuous wave (CW) laser source is modulated by the microwave signal source under test at an electro-optical modulator (EOM), and then split into two branches. A fiber delay line is applied to introduce a time delay between the two branches to realize signal de-correlation. Then, the two optical signals are converted back to the electrical domain, and then phase shifted to obtain two orthogonal signals before mixing with each other for phase noise measurement [5]. In this process, the use of a fiber delay line can effectively improve the phase noise measuring sensitivity and accuracy. However, the system performance is still limited by the electrical processing module. For example, the operation bandwidth may be limited by the electrical phase shifter and/or the electrical mixer. Also, the high complexity of the electrical circuits is a problem. Therefore, it is highly desirable to incorporate more microwave photonic signal processing units into the phase noise measurement system, to provide a wide operation bandwidth, as well as to relax the requirements for complicated electrical circuits.

In this letter, we propose a phase noise measurement system based on the delay-line method using a multifunctional microwave photonic processor which can simultaneously realize the electrical-to-optical conversion, provide a photonic time delay, and control the phase of the output microwave signal. This compact structure saves the use of accurate electrical phase control, and also leads to a large operation bandwidth for the phase noise measurement. The performance of the proposed phase noise measurement system is experimentally investigated. The results can verify the feasibility of the proposed system with a low phase noise floor and a large operation bandwidth.

II. PRINCIPLE

The schematic diagram of the proposed phase noise measurement system is shown in Fig. 1. The dashed box is the microwave photonic processor, which consists of a polarization modulator (PolM), an optical band-pass filter (OBPF), a span of fiber, a polarization controller (PC), a polarizer (Pol) and a photodetector (PD). The microwave signal source under test is divided into two branches. The upper branch is sent to

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The authors are with the Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China (e-mail: zdjmwp@163.com; zhangfangzheng@nuaa.edu.cn; zhoupei@126.com; danzhu@nuaa.edu.cn; pans@ieee.org).

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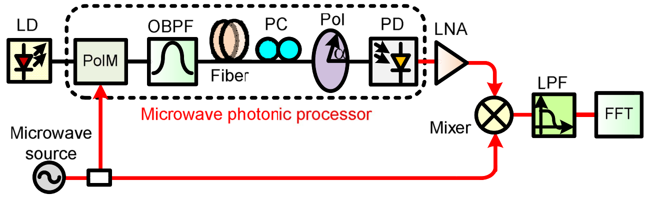

Fig. 1. The schematic diagram of the proposed phase noise measurement system using a microwave photonic processor. LD: laser diode; PolM: polarization modulator; OBPF: optical band pass filter; PC: polarization controller; Pol: polarizer; PD: photodetector; LNA: low noise amplifier; FFT: FFT analyzer.

the microwave photonic processor, to achieve electrical-to-optical conversion, photonic time delay, and accurate phase adjustment. First, a CW light generated by a laser diode (LD) is modulated by the upper branch signal at the PolM, thus electrical-to-optical conversion is realized through polarization modulation. Then, an OBPF is applied to remove one of the first order sidebands of the polarization modulated optical signal and a proper time delay is introduced by the fiber. After that, the optical signal is passed through the PC and polarizer before sent to the PD. By adjusting the PC, the phase of the microwave signal recovered at the PD can be continuously changed in a full 360° range. The principle for the phase adjustment is similar to the microwave photonic phase shifter in [13], except for the fiber delay element. The output signal from the microwave photonic processor is amplified by an electrical low noise amplifier (LNA), and mixed with the lower branch signal at an electrical mixer. Finally, the low frequency signal is extracted by a low pass filter (LPF), and sent to an FFT analyzer for phase noise calculation.

Assuming that the amplitude fluctuation of the microwave signal under test can be ignored, the electrical field emitted by the signal source is written as

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

where V_0 is the constant amplitude, ω is the angular frequency and $\varphi(t)$ is the phase fluctuation. To implement polarization modulation at the PolM, the polarization direction of the CW light is adjusted to have an angle of 45° with one principal axis of the PolM. After the PolM, two phase modulated signals with opposite modulation indices are generated along the two principal axes. Based on the Jacobi-Anger expansions, the optical fields can be expressed as

$$\begin{aligned}\begin{bmatrix} E_x \\ E_y \end{bmatrix} &= \frac{\sqrt{2}}{2}\begin{bmatrix} e^{j(\omega_c t+\beta V(t)+\varphi_0)} \\ e^{j(\omega_c t-\beta V(t))} \end{bmatrix} \\ &= \frac{\sqrt{2}}{2} e^{j\omega_c t}\begin{bmatrix} e^{j\varphi_0}\left[\sum\limits_{m=-\infty}^{+\infty} J_m(\beta V_0) e^{jm[\omega t+\varphi(t)]}\right] \\ \sum\limits_{m=-\infty}^{+\infty} J_m(\beta V_0) e^{jm[\omega t+\varphi(t)+\pi]} \end{bmatrix}\end{aligned} \tag{2}$$

where ω_c is the angular frequency of the optical carrier, J_m is mth-order Bessel function of the first kind, β is the phase modulation index, and φ_0 is the phase difference between E_x and E_y which is determined by the DC bias of the PolM. For small-signal modulation, the higher-order (≥ 2) sidebands in Eq. (2) can be ignored. After removing one of the first-order sidebands by the OBPF and considering a time delay of τ is introduced by the fiber, the optical fields can be denoted as

$$\begin{aligned}\begin{bmatrix} E_x' \\ E_y' \end{bmatrix} &\propto e^{j\omega_c(t-\tau)} \\ &\times \begin{bmatrix} e^{j\varphi_0}\left[J_0(\beta V_0)+J_{-1}(\beta V_0)e^{-j[\omega(t-\tau)+\varphi(t-\tau)]}\right] \\ J_0(\beta V_0)+J_{-1}(\beta V_0)e^{-j[\omega(t-\tau)+\varphi(t-\tau)+\pi]} \end{bmatrix}\end{aligned} \tag{3}$$

If φ_0 is tuned to be $\pi/2$, when the optical signal in (3) passes through the PC and polarizer, the output current at the PD is given as [13]

$$I(t) \propto \cos[\omega t + \varphi(t-\tau) - (2\alpha + \omega\tau)] \tag{4}$$

where α is the angle between the polarization direction of the polarizer and one of the principal axis of the PolM. By tuning the PC to satisfy the following equation,

$$2\alpha + \omega\tau = 2k\pi \tag{5}$$

where k is an integer, (4) can be simplified to be

$$I(t) \propto \cos[\omega t + \varphi(t-\tau)] \tag{6}$$

When this signal is mixed with the microwave signal in the lower branch, the low frequency components filtered by the LPF can be expressed as

$$V_O(t) = k_\varphi \sin[\varphi(t) - \varphi(t-\tau)] \approx k_\varphi[\varphi(t) - \varphi(t-\tau)] \tag{7}$$

where k_φ is the phase-to-voltage conversion factor.

Based on (7), the power spectral density is [5]

$$P_O(f) = 4k_\varphi^2 \sin^2(\pi f \tau) S_\varphi(f) \tag{8}$$

where $S_\varphi(f)$ is the double-sideband phase noise power. If $P_{\mathrm{o}}(f)$ is measured by the FFT analyzer, the single-sideband phase noise power spectrum can be obtained as

$$L(f) = \frac{S_\varphi(f)}{2} = \frac{P_O(f)}{8k_\varphi^2 \sin^2(\pi f \tau)} \tag{9}$$

Since the phase control realized by the microwave photonic processor to satisfy (5) can achieve fast and continuous phase tuning from −180° to 180° in a wide bandwidth with a flat power response [13], and the fiber delay line providing switchable time delay also has a broad bandwidth, the proposed phase noise measurement approach would be accurate and have a large operation bandwidth.

III. EXPERIMENT RESULTS AND DISCUSSION

An experiment is implemented to investigate the performance of the proposed phase noise measurement system. In the experiment, the CW light from the LD has a wavelength of 1550 nm. A PolM (Versawave Inc.) having a bandwidth of 40 GHz and a half-wave voltage of 3.5 V is used to perform polarization modulation. A tunable OBPF (Yenista XTM-50) with an edge slope more than 500 dB/nm is applied to remove the positive sideband of the optical signal, and a 2-km single mode fiber (SMF) is used as the delay line Following the fiber, a PC is placed, and a polarization beam splitter (PBS) with a polarization extinction ratio of more than 35 dB is used as the polarizer. The PD has a bandwidth of 40 GHz and a responsivity of 0.65 A/W. An LNA with a noise figure less than 3 dB and a small-signal gain of 40 dB is used to saturate the mixer. The output signal from the LPF is measured by

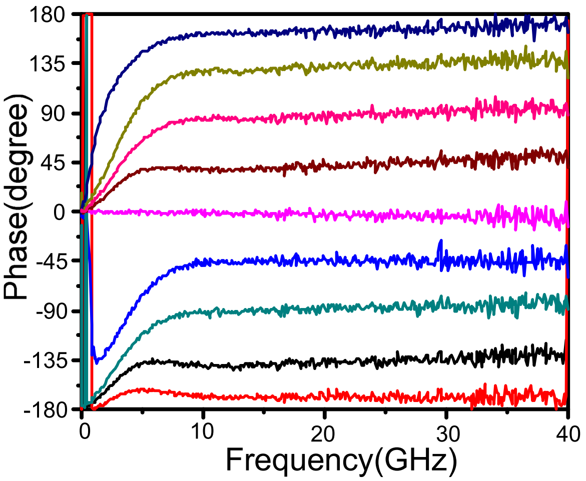

Fig. 2. Measured phase response of the microwave photonic processor.

a baseband signal analyzer and the phase noise is calculated based on Eq. (9).

First, the phase adjusting property of the microwave photonic processor is investigated. Fig. 2 shows the phase responses of the processor measured by a vector network analyzer (VNA, Agilent N5245A) when tuning the PC. In Fig. 2, each curve corresponds to the phase response when the PC is fixed to a certain state. As can be seen, the phase of the input microwave signals from 5 GHz to 40 GHz can be tuned from −180° to 180°. The unideal result for frequencies below 5 GHz is due to the fact that the OBPF cannot effectively remove one of the first-order sidebands because of the limited edge slope. The slight fluctuations in the phase response are mainly due to the random variation of the length of the SMF, which can be eliminated by placing the fiber in a constant environment. To check the accuracy of the proposed phase noise measurement system, the phase noise of a 10 GHz clock signal from a pulse pattern generator (Anritsu MP1763C) is measured by the proposed system. The results are shown in Fig. 3. As a comparison, the phase noise measured by a commercial electrical spectrum analyzer (Agilent E4447A) which has a phase noise measurement utility is also depicted. As can be seen, the two curves in Fig. 3 are very close to each other when the offset frequency is greater than 1 kHz. The difference in the low offset frequency regime is possibly introduced by the flicker noise from the RF amplification stage in the measurement system [14]. The noise floor of the proposed phase noise measurement system is also tested. To do this, the 2 km SMF is replaced by an optical attenuator, thus the time delay is approximately equal to zero and the same optical power attenuation is preserved. The phase noise floor is calculated based on Eq. (9), where τ is the delay of the 2-km SMF [8]. As can be seen from Fig. 4, the noise floor at 10 kHz offset is about −133 dBc/Hz.

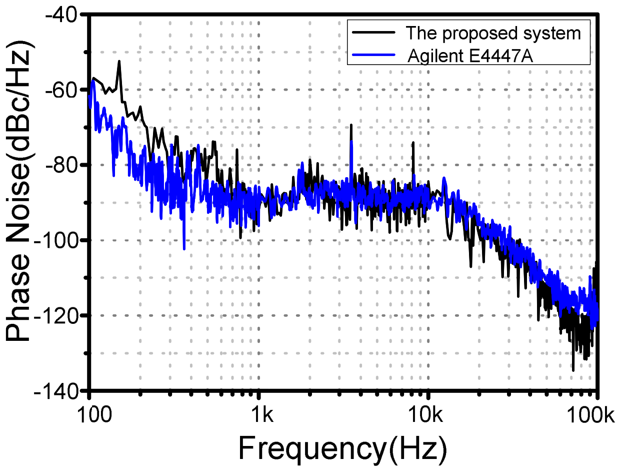

Fig. 3. The phase noise of a 10 GHz clock signal measured by the proposed system (black curve) and measured by Agilent E4447A (blue curve).

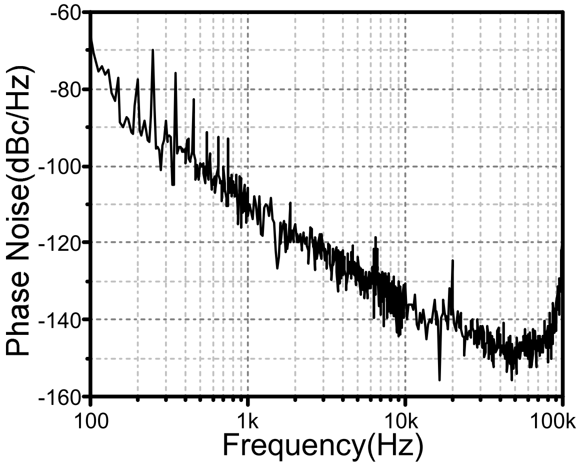

Fig. 4. Measured noise floor of the phase noise measurement system.

Then, the phase noise of a wideband microwave signal source (Agilent 8257D), of which the output frequency is tuned from 5 GHz to 40 GHz with a step of 5 GHz, is measured by the proposed system. During the measurements, only the PC is tuned when the frequency of the signal under test is changed, while the system configuration is fixed. Fig. 5 shows the measured phase noise at 10 kHz frequency offset. The typical values of the phase noise provided by the datasheet of the signal generator is also shown in Fig. 5. As can be seen, the phase noise measured by the proposed system is very close to the typical values, and the difference is kept between −1 and 4 dB/Hz, which can confirm that the proposed phase noise measurement system can operate at a large frequency range.

IV. CONCLUSION

We have proposed and demonstrated a scheme for measuring the phase noise of wideband microwave signal sources using a multifunctional microwave photonic processor. The proposed scheme has a compact structure since electrical-to-optical conversion, time delay and phase control of the microwave signal are all realized by the microwave photonic processor. Besides, a wide operation bandwidth is enabled thanks to the microwave photonic processor. In the experiment, the phase noise of a 10 GHz clock signal is measured accurately and the phase noise floor of the measuring system is lower than −130 dBc/Hz @10 kHz offset. The wide operation bandwidth of the proposed phase noise measurement system

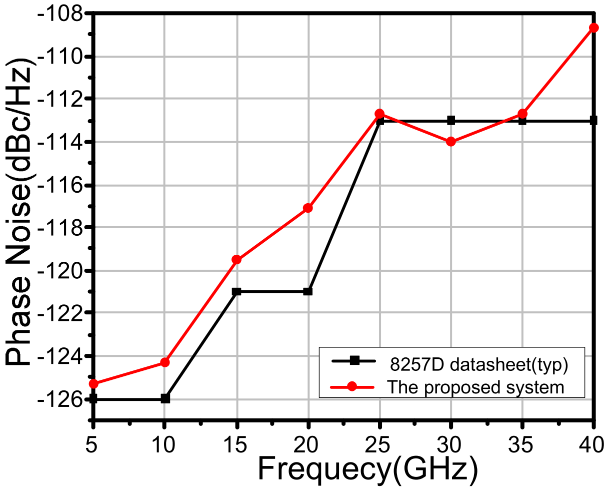

Fig. 5. The phase noise of the signal source (Agilent 8257D) provided by the datasheet (typical value) and the results measured by the proposed system.

is also verified by phase noise measurement of a wideband signal source without rebuilding the system.

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