Photonic-assisted wideband phase noise measurement of microwave signal sources

Fangzheng Zhang, Dengjian Zhu and Shilong Pan✉

A photonic-assisted scheme for the phase noise measurement of microwave signal sources is proposed based on the optical delay-line method. In the proposed scheme, all the microwave signal processing is implemented in the optical domain, and the electrical devices that would limit the operation bandwidth and measurement sensitivity are avoided, leading to a large operation bandwidth and a high sensitivity. The feasibility of the proved phase noise measurement system is experimentally verified. A large operation bandwidth of 5–40 GHz is achieved, and a phase noise floor as low as −140 dBc/Hz at 10 kHz offset is obtained.

Introduction: High-frequency and ultra-low phase noise oscillators have been developing rapidly, e.g. an optoelectronic oscillator can generate a 10 GHz signal with a phase noise as low as −163 dBc/Hz at 6 kHz offset [1]. To measure such a low phase noise, the delay-line method is proposed with relaxed hardware requirements and high measurement sensitivity [2]. Since a large time delay is required in this method, optical fibre is applied to provide the long time delay with negligible loss and high reliability. However, the operation bandwidth of such systems would be limited by the electrical devices, such as the electrical phase shifter and the frequency mixer, which make it not possible to measure the phase noise of wideband signal sources. On the other hand, the unideal performance of the electrical devices also degrades the measurement accuracy and sensitivity. To solve these problems, photonic-assisted phase noise measurement systems are proposed. For example, in [3], the electrical phase shifter in the phase noise measurement system is replaced by a microwave photonic phase shifter. In another system, a microwave photonic mixer is constructed to replace the electrical mixer [4]. However, the photonic-assisted module in these systems could only be a substitute for one of the required electrical components, which means an electrical mixer and a phase shifter are still needed in [3, 4], respectively. Therefore, the operation bandwidth and measurement sensitivity is limited. In this Letter, we propose a photonic-assisted phase noise measurement system which avoids all the electrical devices that would restrict the system bandwidth and measurement sensitivity. The established system can achieve a large operation bandwidth only limited by the bandwidth of the electro-optical modulators, and a good phase noise measurement sensitivity as low as −140 dBc/Hz at 10 kHz.

Principle: Fig. 1 shows the setup of the proposed phase noise measurement system, which consists of a laser diode (LD), a phase modulator (PM), a span of fibre, a polarisation modulator (PolM), a tunable optical bandpass filter (TOBPF), a polarisation controller (PC), a polariser (Pol), a photodetector (PD) and an fast Fourier transform (FFT) analyser. Assuming the microwave signal under test is $E(t) = V_0\cos[\omega t + \varphi(t)]$, where ω is the angular frequency and $\varphi(t)$ is the phase fluctuation, when it passes through a power divider, two signals of $E_1(t) = V_1\cos[\omega t + \varphi(t)]$ and $E_2(t) = V_2\cos[\omega t + \varphi(t)]$ are obtained. The continuous-wave (CW) light from the LD is phase modulated at the PM by $E_1(t)$, and the obtained optical signal is

$$E_{o1}(t) = E_c exp[\mathrm{j}\omega_c t + \mathrm{j}\beta_1 E_1(t)] \tag{1}$$

where E_c and ω_c are the amplitude and angular frequency of the optical field, respectively, and β_1 is the modulation index of the PM. A span of fibre follows to introduce a time delay of τ. The delayed optical signal is

$$E_1(t) = E_c exp[\mathrm{j}\omega_c(t-\tau) + \mathrm{j}\beta_1 E_1(t-\tau)] \tag{2}$$

Then, the optical signal is polarisation modulated at the PolM driven by $E_2(t)$. The optical fields in the two orthogonal polarisation states are

$$\begin{bmatrix} E_\mathrm{x} \\ E_\mathrm{y} \end{bmatrix} = \frac{\sqrt{2}E_c}{2} \mathrm{e}^{\mathrm{j}\omega_c(t-\tau)} \begin{bmatrix} \exp\mathrm{j}[\beta_1 E_1(t-\tau) + \beta_2 E_2(t) + \theta] \\ \exp\mathrm{j}[\beta_1 E_1(t-\tau) - \beta_2 E_2(t)] \end{bmatrix} \tag{3}$$

where β_2 is the modulation index of the PolM and θ is a phase difference between E_x and E_y which is determined by the bias voltage of the PolM. After the PolM, a TOBPF is used to select out the +1st- or the −1st-order optical modulation sideband. When the +1st-order sideband is selected, the optical field can be expressed as

$$\begin{bmatrix} E_\mathrm{x} \\ E_\mathrm{y} \end{bmatrix} \propto \frac{\sqrt{2}E_c}{2} \mathrm{e}^{\mathrm{j}\omega_c(t-\tau)} \begin{bmatrix} \mathrm{e}^{\mathrm{j}\theta}\{jJ_1(\beta_1 V_1)\mathrm{e}^{\mathrm{j}[\omega(t-\tau)+\varphi(t-\tau)]} + jJ_1(\beta_2 V_2)\mathrm{e}^{\mathrm{j}[\omega t+\varphi(t)]}\} \\ jJ_1(\beta_1 V_1)\mathrm{e}^{\mathrm{j}[\omega(t-\tau)+\varphi(t-\tau)]} - jJ_1(\beta_2 V_2)\mathrm{e}^{\mathrm{j}[\omega t+\varphi(t)]} \end{bmatrix} \tag{4}$$

where J_m is the mth-order Bessel function of the first kind. After that, the optical signal is passed through the PC and the polariser before it is sent to the PD. By properly setting the bias of the PolM to let $\theta = \pi/2$, the optical signal after the polariser is

$$\begin{aligned} E_\mathrm{o}(t) &\propto \cos\alpha \cdot E_\mathrm{x} + \sin\alpha \cdot E_\mathrm{y} \\ &= \frac{\sqrt{2}E_c}{2} \mathrm{e}^{\mathrm{j}\omega_c(t-\tau)} \{-\cos\alpha[J_1(\beta_1 V_1)\mathrm{e}^{\mathrm{j}[\omega(t-\tau)+\varphi(t-\tau)]} + J_1(\beta_2 V_2)\mathrm{e}^{\mathrm{j}[\omega t+\varphi(t)]}] \\ &\qquad + \sin\alpha[jJ_1(\beta_1 V_1)\mathrm{e}^{\mathrm{j}[\omega(t-\tau)+\varphi(t-\tau)]} - jJ_1(\beta_2 V_2)\mathrm{e}^{\mathrm{j}[\omega t+\varphi(t)]}]\} \end{aligned} \tag{5}$$

where α is the angle between the polarisation direction of the polariser and one of the principal axes of the PolM. The electrical current from the PD is

$$\begin{aligned} I_\mathrm{PD}(t) &= \eta E_\mathrm{o}(t) \cdot E_\mathrm{o}^*(t) \\ &\propto 2\eta J_1(\beta_1 V_1) J_1(\beta_2 V_2) \cos[\varphi(t) - \varphi(t-\tau) + 2\alpha + \omega\tau] \end{aligned} \tag{6}$$

After adjusting the PC to let $2\alpha + \omega\tau = \pi/2$, (6) can be approximately expressed as

$$I_\mathrm{PD}(t) \propto 2\eta J_1(\beta_1 V_1) J_1(\beta_2 V_2)[\varphi(t) - \varphi(t-\tau)] \tag{7}$$

Based on (7), the power spectral density is

$$S_\mathrm{PD}(f) \propto \sin^2(\pi f \tau) S_\varphi(f) \tag{8}$$

where $S_\varphi(f)$ is the double sideband phase noise power, and $S_\mathrm{PD}(f)$ can be measured by the FFT analyser. Therefore, the single-sideband (SSB) phase noise power spectrum to be measured can be obtained as

$$L(f) = \frac{S_\varphi(f)}{2} \propto \frac{S_\mathrm{PD}(f)}{\sin^2(\pi f \tau)} \tag{9}$$

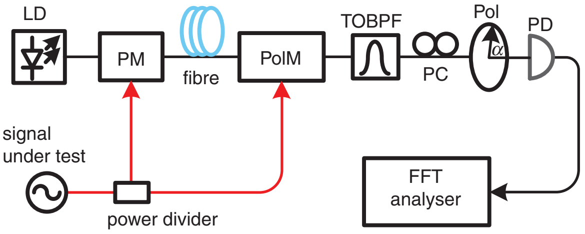

Fig. 1 *Schematic diagram of proposed photonic-assisted wideband phase noise measurement system*

Experimental demonstration: To verify the feasibility of the proposed system, an experiment was implemented based on the setup in Fig. 1. The CW light has a wavelength of 1550 nm. A 40 GHz PM and a 40 GHz PolM (Versawave Inc.) were used to perform phase modulation and polarisation modulation, respectively. A TOBPF (Yenista XTM-50) with an edge slope of more than 500 dB/nm was applied to select the +1st-order optical sideband, and a 2 km single mode fibre (SMF) was used as the delay line. A PC was placed after the TOBPF, and a polarisation beam splitter (PBS) with a polarisation extinction ratio of more than 35 dB was used as the polariser. The PD has a responsivity of 0.85 A/W.

To test the accuracy of the phase noise measurement system, the phase noise of a 10 GHz clock signal generated from a pulse pattern generator (Anritsu MP1763C) was tested, and the result is shown in Fig. 2. As a comparison, the phase noise measured by a commercial spectrum analyser (Agilent E4447) is also included. The two curves in Fig. 2 are very close to each other, especially for a frequency offset of more than 1 kHz, indicating the result measured by the proposed system is reliable. For the frequency offset less than 1 kHz, there is a slight difference, which is mainly due to the flicker noise of the PD. By using a PD with better noise performance, the difference can be minimised. The phase noise floor of the proposed system for measuring a 10 GHz microwave signal source was tested according to the method in [5]. The result is shown in Fig. 3. As can be seen, the noise floor at 10 kHz offset is −140 dBc/Hz, which means good sensitivity is achieved by the proposed system.

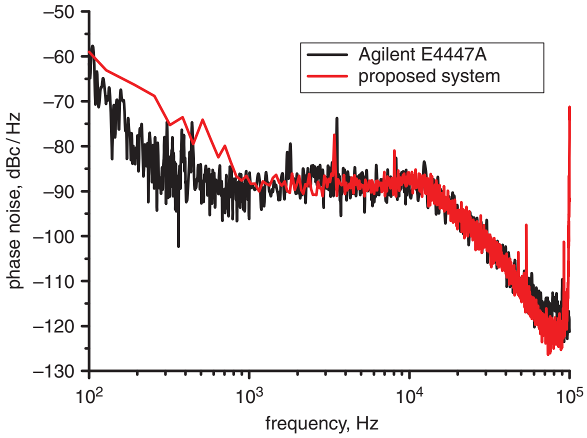

Fig. 2 *Phase noise of 10 GHz clock signal measured by proposed system (red curve) and that measured by commercial spectrum analyser (black curve)*

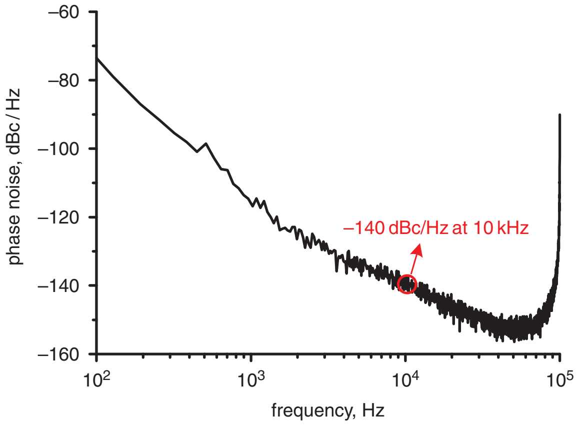

Fig. 3 *Phase noise floor of proposed system*

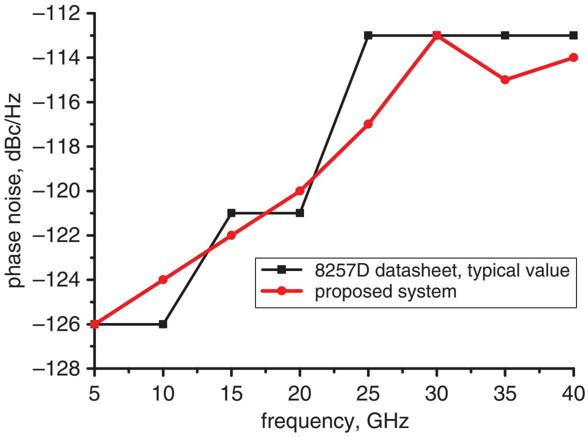

Fig. 4 *Phase noises of wideband signal source (Agilent 8257D) measured by proposed system and provided by datasheet (typical value)*

To check the operation bandwidth of the proposed system, the phase noise of a broadband microwave signal source (Agilent 8257D) was tested by the proposed system. Fig. 4 shows the measured phase noise at 10 kHz offset when the frequency of the signal source changes from 5 to 40 GHz. In Fig. 4, the typical values of the phase noise provided by the datasheet of the signal generator are also included. It is found that the differences between the measured results and the typical values are below 4 dB. This confirms the accuracy of the proposed method once again, and proves that the proposed system can operate at a large frequency range from 5 to 40 GHz. It should be noted that the lower limit of the frequency range is determined by the TOBPF edge slope that should be sharp enough to separate the +1st-order sidebands from the optical carrier, and the upper limit of the measurement frequency range is determined by the bandwidth of the modulators.

Conclusion: We have proposed and experimentally demonstrated a photonic-assisted method to measure the phase noise of microwave signal sources. The proposed system has a large operation bandwidth and high sensitivity, because all the microwave signal processing is performed in the optical domain. An experimental system was established. A large operation in the range from 5 to 40 GHz and a high sensitivity of −140 dBc/Hz at 10 kHz was realised.

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One or more of the Figures in this Letter are available in colour online.

Fangzheng Zhang, Dengjian Zhu and Shilong Pan (*Key Laboratory of Radar Imaging and Microwave Photonics, Ministry of Education, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, People's Republic of China*)

✉ E-mail: pans@ieee.org

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