Wideband and High-Sensitivity Microwave Phase Noise Measurement Based on Photonic Time Delay and Frequency-Conversion Delay Matching

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***Abstract*—A wideband and high-sensitivity microwave phase noise measurement system is proposed and demonstrated. In the experiment, a large operation bandwidth from 10 to 40 GHz is achieved, and the measurement sensitivity reaches -134.13 dBc/Hz@10 kHz.**

***Keywords*—Phase noise measurement, frequency conversion, photonic delay line, microwave photonics.**

I. Introduction

Phase noise is an important index to measure signal fluctuation in the time and frequency domains [1]. With technological innovations in optoelectronic communication, satellite navigation, electronic countermeasures fields and the emergence of high-performance microwave oscillators, how to achieve large-bandwidth, high-sensitivity phase noise measurement (PNM) has become a key challenge [2,3]. To date, a number of PNM methods have been designed and carried out to accurately measure the phase noise of microwave signal sources, including the direct spectrum method, phase detector method, and frequency discriminator method. Among these methods, the frequency discriminator method is more attractive, since it can eliminate the requirement of a low phase noise reference oscillator [4]. However, the measurement sensitivity of this method is related to the time delay, which is limited by the large loss of electrical cables. Fortunately, photonic techniques have been introduced to develop microwave or millimeter-wave phase noise analyzers, i.e., a photonic-delay line PNM method has been proposed with a high measurement sensitivity, where a section of optical fiber is applied to provide a long-time delay with negligible loss [4]. In recent years, much effort has been devoted to improving the overall performance of the photonic-delay line PNM system. For instance, the digital phase demodulation technique is introduced to eliminate the calibration procedure [5]. To enhance the measurement sensitivity, optical frequency comb and carrier suppression interferometer techniques have been adopted [6,7]. In addition, to meet the developing trend of multi-functional integration, the basic phase noise measurement system also integrates microwave signal generation or frequency measurement functions [8,9]. Nevertheless, a problem with most of the previous photonic-delay-line-based schemes is that the use of electrical devices (e.g., electrical mixers and phase shifters) limits the operational bandwidth. To address this problem, microwave photonic phase shifter and microwave photonic mixer have been employed to replace the electrical phase shifter and mixer of a traditional photonic-delay line PNM system to extend the operational bandwidth [10,11]. Unfortunately, all-optical PNM schemes, which realize all microwave signal processing functions in the optical domain, have rarely been reported [12]. In [12], a specially customized electro-optical polarization modulator is used for phase shifting, which inevitably limits the further expansion of the operational bandwidth.

In this paper, a wideband phase noise analyzer based on frequency-conversion delay matching is experimentally demonstrated. The prominent advantage of this scheme lies in that the signal under test (SUT) can be processed at a lower frequency range by frequency conversion, thus relieving the limitation of electrical devices on operational bandwidth. Furthermore, the additional phase noise introduced by the reference source can be effectively eliminated through matching the time delay of two down-conversion branches. In the proof-of-concept experiment, accurate phase noise measurement of SUTs is achieved in a frequency range of 10–40 GHz, and a phase noise floor as low as -134.13 dBc/Hz at 10 kHz is obtained. The results confirm that the proposed system is capable of evaluating microwave signals with a large frequency range and very low phase noise.

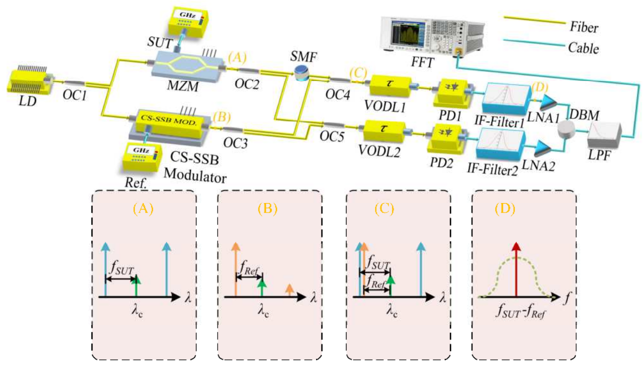

Fig. 1. Schematic diagram of the proposed phase noise measurement system based on photonic time delay and frequency-conversion delay matching. LD: laser diode. OC: optical coupler. MZM: Mach–Zehnder modulator. CS-SSB modulator: carrier-suppressed single-sideband modulator. SUT: signal under test. Ref: reference source. SMF: single-mode fiber. VODL: variable optical delay line. PD: photodetector. IF-Filter: intermediate frequency filter. LNA: low noise amplifier. DBM: double balanced mixer. LPF: low pass filter. FFT: fast Fourier transform analyzer.

II. Principle

Fig. 1 provides a schematic diagram of the proposed PNM system based on frequency-conversion delay matching and photonic time delay. In order to introduce a long time delay in the optical domain, an optical carrier from a laser diode (LD) is modulated by the SUT at a Mach–Zehnder modulator (MZM1). Then, the intensity-modulated optical signal is split into two branches, and a relative time delay is introduced via a section of single-mode fiber (SMF). Compared with the typical photonic-delay line method in [4], the proposed method has an additional frequency-conversion module, consisting of a reference source, a carrier-suppressed single-sideband (CS-SSB) modulator, a pair of photodetectors (PDs), and intermediate frequency (IF) filters. The CS-SSB modulator is realized by an MZM (MZM2) biased at the minimum transmission point (MITP), an optical bandpass filter (OBPF1), an erbium-doped fiber amplifier (EDFA), and another OBPF2. OBPF1 and OBPF2 are applied to select the +1st-order sideband and suppress the amplified spontaneous emission (ASE) noise of the EDFA, respectively. Here, the EDFA is employed to boost the optical power of the extracted sideband. In the photonic microwave frequency-conversion module, the intensity-modulated optical signals in both branches are converted to the electrical domain, and then mixed in the double balanced mixer (DBM). Before that, two variable optical delay lines (VODLs) are required for delay matching and realizing the phase orthogonal condition, respectively. By sending the output signal into a fast Fourier transform (FFT) analyzer, the phase noise of the SUT is calculated. It is worth noting that the additional phase noise introduced by the reference source can be effectively suppressed by matching the time delay of two down-conversion branches, thus eliminating the need for a high-performance reference source to achieve high measurement sensitivity.

III. Experimental Setup and Results

In the experiment, a commercial LD with a center wavelength of 1550.12 nm and a maximum output power of 16 dBm is employed. Both MZMs have a bandwidth of 30-GHz. In the CS-SSB modulator, MZM2, OBPF1, an EDFA and OBPF2 are cascaded. OBPF1 with a roll-off factor of 400 dB/nm and OBPF2 with a bandwidth of 0.78 nm are employed to select the required +1st-order modulation sideband and suppress the ASE noise of the EDFA, respectively. Two VODLs, which can provide a delay range from 0 to 1500 ps and a resolution of 10 fs, are applied. The 3-dB bandwidths of PD1 and PD2 are 20 GHz and 30 GHz, respectively, while both PDs have a responsivity of 0.85 A/W. The passband of both IF-Filters is from 800 to 1000 MHz. Two low noise amplifiers (LNAs) with an operational frequency range of 700 to 2000 MHz and a gain of 36 dB are used. The RF/LO frequency range of the DBM is from 0.5 to 40 GHz. The LPF has a 3-dB cutoff frequency of 5 MHz. An FFT analyzer (Keysight N9020A) is used to collect the signal after LPF. The electrical spectrum is characterized by a 40-GHz commercial signal source analyzer (SSA, R&S FSV40). The optical spectrum is monitored by an optical spectrum analyzer (OSA, Ando AQ6317B) with a resolution of 0.02 nm.

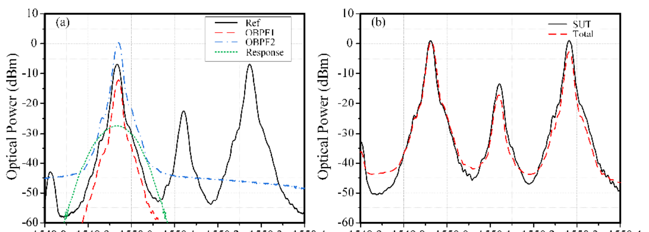

Fig. 2. (a) Optical spectra after MZM2 (black), OBPF1 (red), OBPF2 (blue) and the transmission response of BPF1 (green). (b) Optical spectra after MZM1 (black) and OC4 (red).

To investigate the frequency-conversion performance of the proposed system, a 20-GHz SUT and a 19.1-GHz reference signal are separately generated from two commercial signal sources (R&S SMA100B; Anritsu MG3692B). The output powers of the SUT and reference signal are 16.7 dBm and 18.5 dBm, respectively. The optical spectra after the MZMs and OBPFs, as well as the transmission response of the optical filters, are plotted in Fig. 2. As shown in Fig. 2(a), the optical signal is carrier-suppressed double-sideband (CS-DSB) modulated by the 19.1 GHz reference signal. OBPF1 selects the +1st-order sideband, while the other optical components are significantly suppressed to reduce the influence of interference. After boosting the optical power with an EDFA and suppressing the ASE noise with OBPF2, the optical power of the +1st-order sideband amounts to 0.14 dBm. As shown in Fig. 2(b), the optical signal is also CS-DSB modulated by a 20 GHz SUT, and the optical power of both ±1st-order sidebands is approximately 0.14 dBm. Due to the 0.02 nm resolution of OSA, it is difficult to distinguish the +1st-order sideband of the SUT from that of the reference source. The electrical spectra after PDs and IF-Filters are shown in Fig. 3. In Fig. 3(a), after optical-to-electrical conversion, the desired down-conversion signal is generated with a frequency of 900 MHz. As shown in Fig. 3(b) and 3(c), unwanted signals are removed, and no obvious spur components are observed. The results confirm that photonic microwave frequency-conversion is successfully realized.

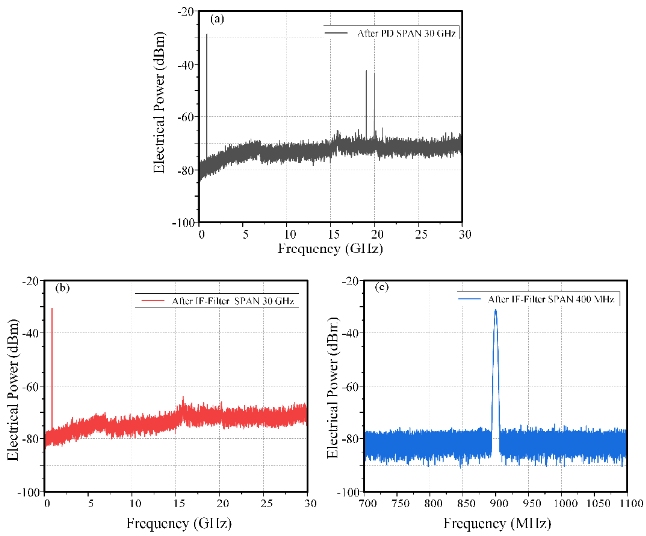

Fig. 3. Electrical spectra after the (a) PD, span: 30 GHz; (b) IF-Filter span: 30 GHz; and (c) IF-Filter span: 400 MHz.

Then, the measurement accuracy of the proposed system is verified by testing the phase noise of a 10 GHz microwave oscillator (BZB10G). Fig. 4(a) provides a comparison of the measurement results by the proposed PNM system and R&S FSV40. Compared with the results of the commercial SSA (R&S FSV40), the proposed PNM system has consistent phase noise results at offset frequencies above 1 kHz, which proves the reliability of the proposed PNM system. The slight difference in the lower offset frequency regime is possibly attributed to the infinite response of the frequency discriminator method at zero offset frequency. This problem can be alleviated by increasing the length of the delay line, however, at the sacrifice of the measurement range. The performance comparison between the SUT (R&S SMA100B) and the reference source (Anritsu MG3692B) is shown in Fig. 4(b). Although a commercial microwave source with worse performance is used as the reference source, the phase noise of the SUT with better performance can still be accurately measured after matching the time delay of both branches, which proves that the phase noise of the reference source has been effectively suppressed. Then, the phase noise floor of the proposed PNM system is also measured according to the method in [4], i.e., the 2 km SMF is replaced by an optical attenuator with the same loss. For comparison, the phase noise floor of the commercial SSA is plotted in Fig. 4(c). The phase noise floor at a 10 kHz offset is measured to be -134.13 dBc/Hz at 20 GHz, which is much better than that of the R&S FSV40 (approximately −98 dBc/Hz @ 10 kHz at 20 GHz), proving the high measurement sensitivity of our PNM system.

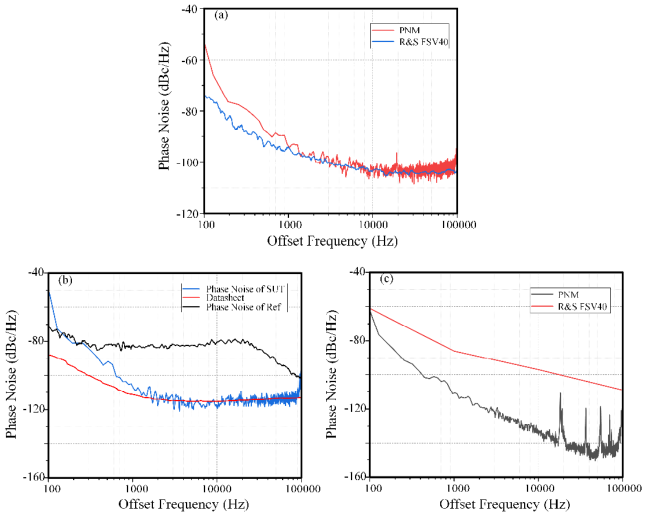

Fig. 4. (a) Phase noise of a 10 GHz microwave oscillator measured by the proposed system (red) and that measured by a commercial signal analyzer R&S FSV40 (blue). (b) Phase noise of the 20 GHz SUT measured by the proposed system with delay matching (blue), according to its datasheet (red), and the phase noise of the reference source measured by a commercial SSA R&S FSV40 (black). (c) Phase noise floor of the proposed system (black) and R&S FSV40 (red).

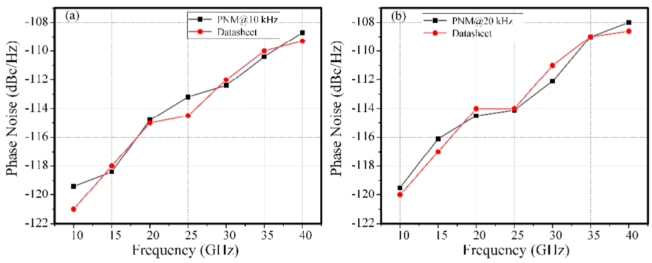

Fig. 5. Phase noises of a wideband signal source (R&S SMA100B) measured by the proposed system (black) and provided by the datasheet (red) at offset frequencies of (a) 10 kHz and (b) 20 kHz.

To check the operational bandwidth of the proposed system, a commercial wideband microwave generator (Anritsu MG69367B) is used as a reference source to measure the phase noise of a wideband microwave signal source (R&S SMA100B). The frequency difference between the reference signal and the SUT is fixed at 900 MHz when the SUT is adjusted from 10 to 40 GHz with a step of 5 GHz. The comparisons between the measured phase noise and the typical values provided by the datasheet at 10 kHz and 20 kHz offsets are shown in Fig. 5. It can be seen that the measurement results are very consistent with those in the datasheet, and the differences are kept within 2 dB, which proves that the proposed system can operate accurately from 10 to 40 GHz. It should be noted that the minimum operational frequency is determined by the OBPF edge slope, and the maximum operational frequency is restricted by the bandwidth of the modulators, which are hopefully enhanced.

IV. Conclusion

We have proposed and demonstrated a novel PNM method based on photonic time delay and frequency-conversion delay matching. By using a photonic microwave frequency-conversion module, the SUT is down-converted and can be processed at a lower frequency range, thus relieving the limitation of electrical devices on operational bandwidth. Furthermore, by matching the time delay of two down-conversion branches, the additional phase noise introduced by the reference source can be effectively suppressed, eliminating the need for a high-performance reference source and improving the measurement sensitivity. In the experiment, accurate phase noise measurement of SUTs is achieved in a frequency range of 10-40 GHz, and a phase noise floor as low as -134.13 dBc/Hz at 10 kHz is obtained.

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