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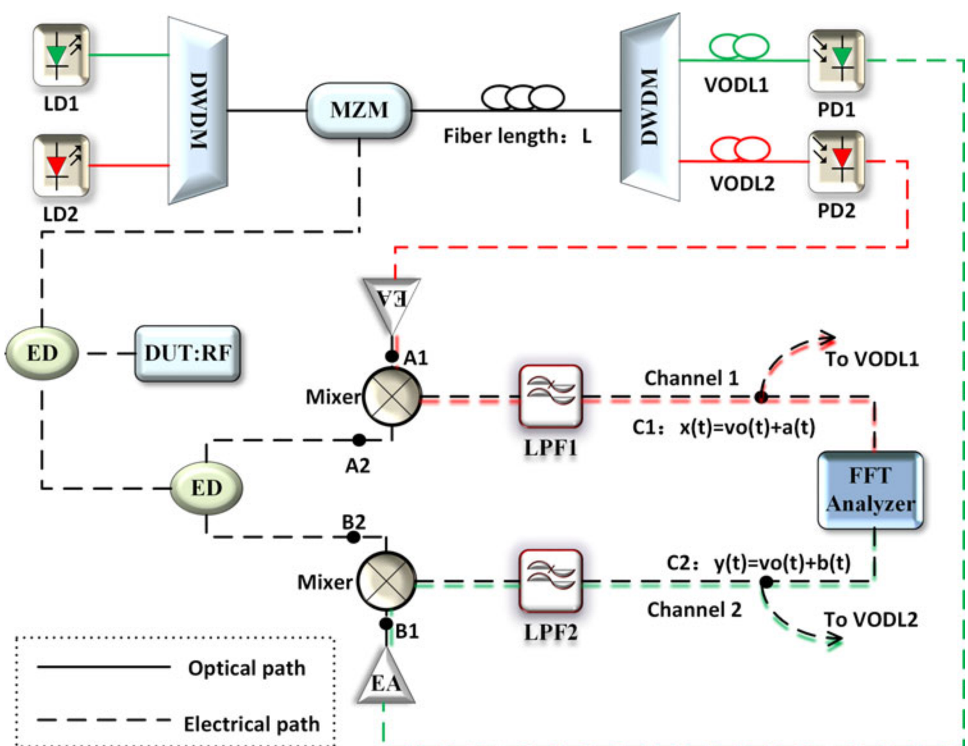

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Photonic-Delay Line Cross Correlation Method Based on DWDM for Phase Noise Measurement

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Abstract: A dual photonic-delay line cross-correlation method for phase noise measurement of microwave signal based on dense wavelength division multiplexing (DWDM) is proposed and experimentally demonstrated. The kilometer-long delay fiber is used together by the two mutually independent channels through the DWDM technology, which makes it easier to get the same delay between two channels. And it reduces the cost of the system by reducing the use of several kilometers of fiber and a Mach–Zendher modulator. Then, it uses variable optical fiber delay lines to replace the electronic phase shifters and a broader operation bandwidth can be obtained. A lower phase noise floor has been obtained by more averaging of the cross-correlation spectrum. In the experiments, the phase noise of a 10-GHz microwave signal has been measured accurately. A large operation bandwidth of 4–11 GHz is achieved and a measurement phase noise floor of -152.6 dBc/Hz at 10 kHz offset at 10 GHz in a 20 μs delay measurement system is realized by averaging 100 times.

Index Terms: Microwave photonics, phase noise measurement, cross correlation, dense wavelength division multiplexing (DWDM).

1. Introduction

Phase noise, which is of major concern in microwave sources such as electrical oscillators [1] and optoelectronic oscillators [2], [3], has attracted a lot of attentions in both aspects of theoretical analysis [4]–[9] and measurement system [10] during the past decades because it may seriously degrade the performance of the systems such as radar, wireless communication system, multi-channel receiver, and so on. To meet the growing measurement demand in high performance microwave sources, which have higher frequency, larger tuning range and extremely low phase noise, a large amount of conventional methods for phase noise measurement have been designed and implemented, for instance, direct spectrum technique [11]–[13], phase detector technique [14], frequency discriminator method [15]–[17], two-channel cross-correlation technique [18]–[20], etc. Recently, microwave photonic technologies such as photonic-delay line [21]–[26], microwave photonic phase shifter [27], [28], microwave photonic frequency down-converter [29], [30], electro-optic comb [31], and so on, which are in advantages of low loss, wide band and the ability of working in any range of microwave frequencies, have been used in phase noise measurement, with the results that the measurement range of frequency and sensitivity are greatly improved.

Direct spectrum technique [11]–[13] is the simplest method for phase noise measurement, which usually reads the spectrum directly from a spectrum analyzer and calculates the ratio of the power level (within 1 Hz bandwidth) of a specified offset frequency to the total power level of the carrier. However, it cannot differentiate amplitude noise (AM noise) and phase noise (PM noise), and the carrier power limits the measurement dynamic range.

At the same time, phase detector technique [14] is implemented for a better distinguish between AM noise and PM noise, where a phase detector is used to convert phase difference of the signal under test and the reference signal into a voltage with an average value of 0 V, note that the phase difference between the two signals is $\pi/2$. What is more, a phase locked loop (PLL) is usually introduced into the phase detector technique to orthogonally lock the two signals. According to the operational mechanism of the phase detector technique, it takes advantages of wonderful measurement sensitivity, wide signal frequency range and rejection of AM noise, but on the other hand it needs an excellent performance reference source with a widely tunable range to improve the measurement performance.

To eliminate the limitation of the reference source, frequency discriminator method [15]–[17], which can be implemented by cavity resonators, radio frequency (RF) bridges or a delay line [10], has been forward, a baseband analyzer is used to measure the low frequency voltage fluctuations converted by the frequency fluctuations of the source. In particular, the delay line based frequency discriminator method does not need a second reference source when a high sensitivity is achieved. However, the loss of the cable limits the length of coaxial cables and compromises the measurement sensitivity. Encouragingly, two-channel cross-correlation techniques [18]–[20] provide an effective way to reduce the phase noise floor through the cancellation of the incoherent noise of the individual measurement systems at the expense of measurement speed.

Recently, microwave photonic techniques which have been developed since more than ten years [32], [33] were applied in phase noise measurement system [21]–[31]. Compared with the phase noise measurement systems mentioned in [11]–[20], the photonics techniques based phase noise measurement systems have advantages of lower phase noise floor at higher frequency and wider range of measurements, which benefit by the photonic techniques advantages such as low loss, wide band and the ability of working in any range of microwave frequencies. To overcome the high loss of coaxial cable, the photonic-delay line technique is introduced into the frequency discriminator method and a longer time delay is obtained, then, a higher measurement sensitivity is realized [21], [22]. In addition, microwave photonic phase shifters based on a polarization modulator (PolM) [27] and a dual-drive Mach-Zehnder modulator (MZM) [28] respectively, microwave photonic down-converters based on a MZM [29] and a PolM [30] individually, are introduced into the photonic-delay line assisted phase noise measurement systems to implement wide-band phase noise measurement systems. And a real time high sensitivity phase noise measurement system based on electro-optic comb is realized [31], it uses the higher order comb modes from an electronic-optic comb to enhance the measurement sensitivity of phase noise. Except the single channel phase noise measurement systems mentioned above [21], [22], [27]–[31], dual photonic-delay line cross correlation methods have been proposed in [23]–[26], where the phase noise floor is reduced by eliminating the uncorrelated noise of the two measurement systems. Note that the delay of the two channels must be the same for this scheme to work effectively [23]. However, it is a challenging task to ensure the two long fibers with length of over many kilometers used in the two channels individually remain consistent.

In this paper, we proposed and experimentally demonstrated a phase noise measurement system based on dual photonic-delay line cross correlation method using dense wavelength division multiplexing (DWDM) and variable optical fiber delay line (VODL). The long fiber with length of many kilometers, which provides a long delay time to reduce the phase noise floor of phase noise measurement system, is used by two channels simultaneously in terms of DWDM. This structure makes it easier to get the same delay between two channels and saves many kilometers of fiber. In addition, two VODLs are used to control the phase of the signals, which saves the use of electrical

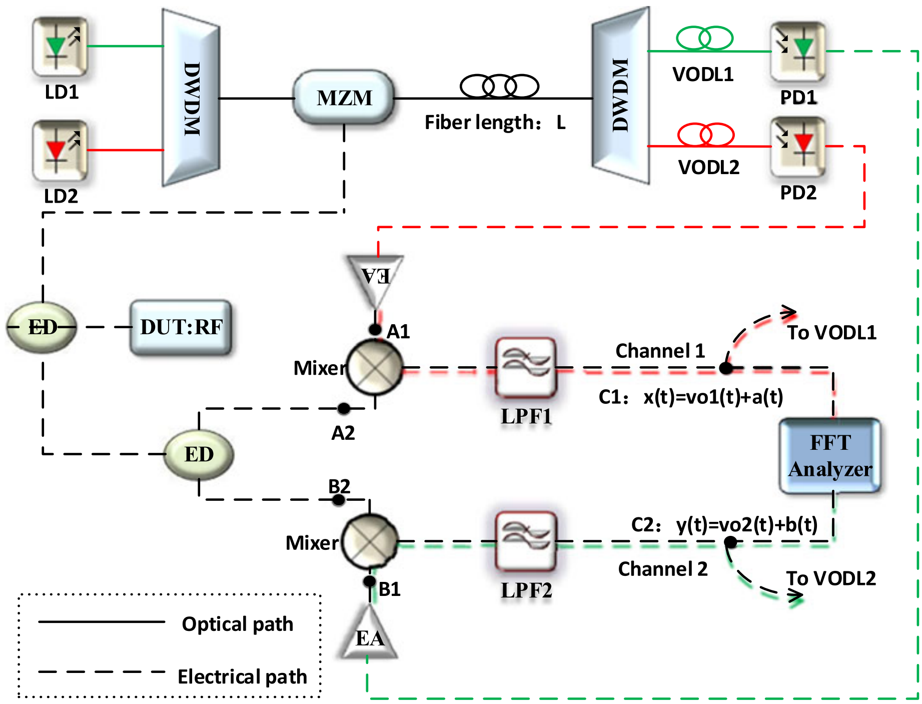

Fig. 1. The schematic diagram of the proposed phase noise measurement system. LD: laser diode; DWDM: dense wavelength division multiplexer; MZM: Mach-Zendher modulator; VODL: variable optical delay line; PD: photoelectric detector; EA: electrical amplifier; LPF: low-pass filter; ED: electrical divider.

phase controllers and leads to a larger working bandwidth for the phase noise measurement system. And a phase noise measurement system which has a phase noise floor of −152.6 dBc/Hz at 10 kHz offset was realized when the signal under test has a frequency 10 GHz. In addition, an operation bandwidth of 4–11 GHz was realized in this paper.

2. Principle

Fig. 1 shows the schematic diagram of the presented dual photonic-delay line cross correlation method for phase noise measurement. It includes two independent photonic-delay line based phase noise measurement systems with same delay time, moreover, the long fiber which provides longer delay time is in common used by two independent photonic assisted phase noise measurement systems through DWDM. The microwave source under test is divided into two branches by an electrical divider, one is introduced to the microwave photonic link which is used to achieve electrical-to-optical conversion, photonic time delay and accurate phase adjustment, the other one is continued to be divided into two branches and sent to the mixers respectively. In both phase noise measurement systems, a light from a LD is introduced into a MZM, of which the output is passed through a long optical fiber which is shared by two phase noise measurement systems with DWDM, a VODL which is used to achieve accurate phase adjustment, and detected with a PD. The output of the PD is amplified and mixed with the signal that passes directly through two EDs. Then the intermediate-frequency (IF) signal is passed a low-pass filter (LPF). Finally, the two low frequency signals from two independent phase noise measurement systems respectively are introduced to a dual-ports fast Fourier transform (FFT) analyzer simultaneously for phase noise calculation. Note that the low frequency signals after the LPFs are returned to the VODLs to control the signals at points A1 (B1) and A2 (B2) are orthogonal, the dc component of the low frequency signals after the LPFs is zero when the phase difference between the two input signals is 90 degrees, otherwise the signals after the LPFs will have a dc component.

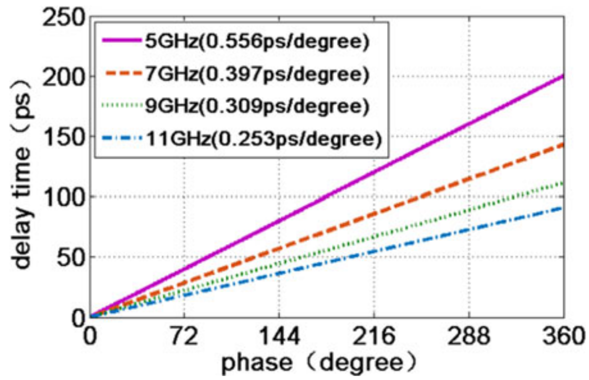

Fig. 2. The relationship between the phase of microwave signal and delay time of optical fiber.

The VODL adjusts the phase accurately by controlling the delay time. And the relationship between the phase of microwave signal and delay time of optical fiber is in the following formula and shown as Fig. 2. For instance, when the frequency of signal is 10 GHz, a continuously changed in a full 360 degrees range can be achieved by tuning the delay line in a range of 100 ps.

$$t(\varphi) = \frac{\varphi}{360^\circ \cdot f} \tag{1}$$

Where φ and f are phase and frequency of microwave signal respectively, $t(\varphi)$ is the delay time of the delay line.

The amplitude noise comes from the oscillators under test cannot be rejected by correlation [34]. However, the amplitude noise of most oscillators is far less than the phase noise of them [27], and we assume that the amplitude noise of the oscillators under test is far less than the phase noise of them and the amplitude fluctuation of the microwave source under test can be ignored, then the microwave signal is given as bellow:

$$v_i(t) = V_0 \cos[\omega_0 t + \varphi_i(t)] \tag{2}$$

Where V_0 is the constant amplitude, ω_0 is the angular frequency and $\varphi_i(t)$ is the phase fluctuation. When the signal pass through the single delay line based frequency discriminator system and the signals in two branches maintain orthogonal to each other, the low frequency components after the LPF can be expressed as Eq. (3a). Considering that phase noise of the signals $\varphi_i(t)$ and $\varphi_i(t-\tau)$ are very small, $v_o(t)$ is approximated by Eq. (3b).

$$v_o(t) = k_\varphi \sin[\varphi_i(t) - \varphi_i(t-\tau)] \tag{3a}$$

$$v_o(t) = k_\varphi [\varphi_i(t) - \varphi_i(t-\tau)] \tag{3b}$$

Where k_φ is the phase-to-voltage conversion factor, τ is the delay time of the long photonic delay line. According the detail analysis in [21], the power spectrum is shown as bellow:

$$S_{\varphi o}(f) = 4k_\varphi^2 \sin^2(\pi f \tau)\, S_{\varphi i}(f) \tag{4}$$

Where $S_{\varphi i}(f)$ is the double-sideband phase noise power of the microwave signal under test. The single-sideband phase noise can be written as:

$$L(f) = \frac{S_{\varphi i}(f)}{2} = \frac{S_{\varphi o}(f)}{8k_\varphi^2 \sin^2(\pi f \tau)} \tag{5}$$

The two-channel measurement system is shown as the schematic diagram of Fig. 1, where $a(t)$ and $b(t)$ are the background noise of the channel1 and channel2 respectively. According [21], the sources of noise such as white noise, flicker noise of amplifier and mixer, contamination from amplitude noise, flicker noise of the microwave photonic channel, and so on, have been analyzed in detail. And the result shows that the major factor of the phase noise is flicker noise of typical microwave amplifiers which stay independent in the two channels. In addition, the common element fiber in the measurement path may introduce a coherent noise term that may limit the noise reduction capabilities of the setup. However, the noise contributed by the fiber is far less than the thermal noise of the amplifier [23], thus the noise of the fiber can be ignored in the analysis process. It means that the background noise of channel1 and channel2 can be supposed to statistically independent, in addition, the phase noise of the signal under test is statistically independent of the background noise $a(t)$ and $b(t)$. Thus, the observed signals and the Fourier transform at points C1 and C2 in Fig. 1 can be written as Eq. (6) according to the description in [35]:

$$\begin{aligned} x(t) &= v_{o1}(t) + a(t) \leftrightarrow X(f) = S_{\varphi O1}(f) + A(f) \\ y(t) &= v_{o2}(t) + b(t) \leftrightarrow Y(f) = S_{\varphi O2}(f) + B(f) \end{aligned} \tag{6}$$

Where $S_{\varphi O1,2}(f)$, $A(f)$ and $B(f)$ are the Fourier transform of $v_{o1,2}(t)$, $a(t)$ and $b(t)$. The cross-spectrum S_{yx} can defined as:

$$\begin{aligned} E\left\{S_{yx}(f)\right\} &= \frac{1}{T}E\left\{Y \cdot X^*\right\} \\ &= \frac{1}{T}E\left\{\left[S_{\varphi O2} + B\right] \cdot \left[S_{\varphi O1} + A\right]^*\right\} \\ &= \frac{1}{T}\left[E\left\{S_{\varphi O2} \cdot S^*_{\varphi O1}\right\} + E\left\{S_{\varphi O2} \cdot A^*\right\} + E\left\{B \cdot S^*_{\varphi O1}\right\} + E\left\{B \cdot A^*\right\}\right] \\ &= \frac{1}{T}E\left\{S_{\varphi O2} \cdot S^*_{\varphi O1}\right\} \end{aligned} \tag{7}$$

Where '$*$' stands for complex conjugate, $E\{\}$ is the expected value operator, T is the measurement time, and the hypothesis of statistical independence gives $E\{S_{\varphi O2} \cdot A^*\} = 0, E\{B \cdot S^*_{\varphi O1}\} = 0$ and $E\{B \cdot A^*\} = 0$. Considering Eq. (4) and assuming the phase-to-voltage conversion factors are the same, the cross-spectrum S_{yx} can be rewritten as:

$$\begin{aligned} E\left\{S_{yx}(f)\right\} &= \frac{1}{T}E\left\{S_{\varphi O2} \cdot S^*_{\varphi O1}\right\} \\ &= \frac{\sin^2\left[\pi f\left(\tau + d\tau\right)\right]}{\sin^2\left(\pi f \tau\right)} \cdot \frac{1}{T}E\left\{S_{\varphi O1} \cdot S^*_{\varphi O1}\right\} \\ &= \frac{\sin^2\left[\pi f\left(\tau + d\tau\right)\right]}{\sin^2\left(\pi f \tau\right)} \cdot S_{\varphi O1 \varphi O1} \end{aligned} \tag{8}$$

Where $d\tau$ is the delay differential of the two channels. Then we replace the expectation with the average on m measured spectra:

$$\begin{aligned} \left\langle S_{yx}(f)\right\rangle_m &= \frac{1}{T}\left\langle Y \cdot X^*\right\rangle_m \\ &= \frac{1}{T}\left\langle\left[S_{\varphi O2} + B\right] \cdot \left[S_{\varphi O1} + A\right]^*\right\rangle_m \\ &= \frac{1}{T}\left[\left\langle S_{\varphi O2} \cdot S^*_{\varphi O1}\right\rangle_m + \left\langle S_{\varphi O2} \cdot A^*\right\rangle_m + \left\langle B \cdot S^*_{\varphi O1}\right\rangle_m + \left\langle B \cdot A^*\right\rangle_m\right] \\ &= H\left(f, \tau, d\tau\right) \cdot S_{\varphi O1 \varphi O1} + O\left(\sqrt{1/m}\right) \end{aligned} \tag{9}$$

Where $O()$ means 'order of'. Owing to statistical independence, the cross terms decrease proportionally to $m^{-1/2}$. The coefficient $H(f, \tau, d\tau)$ is given by:

$$H\left(f, \tau, d\tau\right) = \frac{\sin^2\left[\pi f\left(\tau + d\tau\right)\right]}{\sin^2\left(\pi f \tau\right)} \tag{10}$$

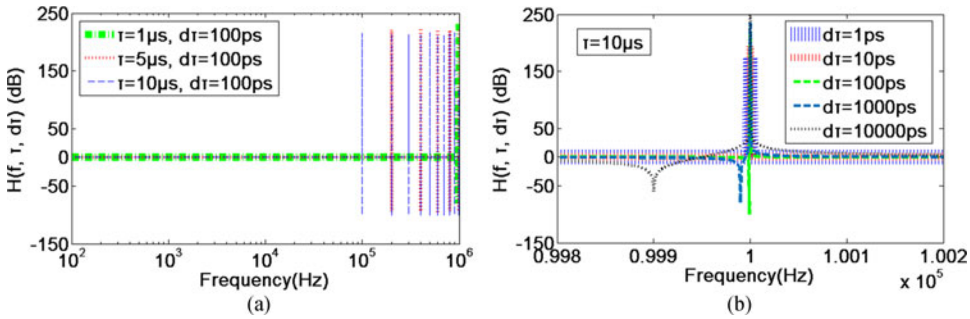

Fig. 3. The coefficient $H(f, \tau, d\tau)$ with different (a) τ and (b) $d\tau$.

Fig. 3 is the coefficient $H(f, \tau, d\tau)$ in different time delays and different delay differentials respectively. It shows that the delay differential between the two channels would influence the measurement of phase noise. In Fig. 3(a), when the time delays of the two channels are not same, $H(f, \tau, d\tau)$ has a serious of step changes at $f = n/\tau$, with integer $n \geq 1$. The experiment results are not useful in the adjacent region of these step changes. And the larger the delay differential leads the more serious the result distortion as shown in Fig. 3(b). Thus, controlling the time delays of the two channels are same can make sure the phase noise measurement system works effectively.

If the delay differential of the two channels $d\tau = 0$, the coefficient $H(f, \tau, d\tau) = 1$, which means when the time delays of the two channels are same, the Eq. (9) can be rewritten as:

$$\langle S_{yx}(f)\rangle_m = S_{\varphi O1 \varphi O1} + O\left(\sqrt{1/m}\right) \tag{11}$$

According to Eq. (11), if the delays of the two channels are same, the cross-correlation method based phase noise measurement system could work effectively. And the measurement sensitivity can be enchanted proportionally to $m^{-1/2}$. For instance, a 10-dB improvement on the single-channel noise coasts a factor of $m = 100$ in averaging. Note that the convergence effect is not considered here, because it affects the measurement sensitivity only when the factor m is big enough [35].

3. Experimental Results and Discussions

A proof-of-concept experiment is carried out based on the setup in Fig. 1. A laser source with wavelength of 1550.12 nm is applied as LD1 and LD2 has a wavelength of 1550.92 nm, both laser sources have a power of 10 dBm. A polarization-maintaining fiber pigtailed DWDM is used before the modulator. The delay-line fiber used in the proposed system is a single-mode optical fiber (SMF-28e). The modulator is a single-drive intensity $LiNbO_3$ modulator (OCLARO F-10) which has a 3-dB bandwidth of 11 GHz and insertion loss of 6 dB. Both PDs have responsivity of 0.8 A/W and 3-dB bandwidth of 11 GHz. And both the VOLDs have a tuning range of 600 ps and a resolution of 39.6 fs. The two EAs, two mixers and EDs have response of 40 GHz, 18 GHz and 18 GHz, respectively. The LPFs have the same passband of DC to 1.9 MHz. The FFT analyzer is realized by a multi-channel oscilloscope (Agilent DSO-X 3034A) which is used to record waveform data and a computer which is used to calculate the cross-correlation power spectrum and phase noise spectrum.

To verify the proposed phase noise measurement system can work effectively, the phase noise of a 10 GHz microwave signal from a commercial microwave signal generator (Anritsu MG3693C) is tested as shown in Fig. 4. The phase noise measurement system with different length of delay-line fiber 1 km (Fig. 4(b), plot A), 2 km (Fig. 4(b), plot B) and 4 km (Fig. 4(b), plot C) have been tested. And the phase noise measured by a commercial spectrum analyzer (Anritsu MS2725C) has been tested as a comparison (Fig. 4(a), plot B). The result shows that the curves in Fig. 4 are close to each other, it means the result measured by this phase noise system is reliable.

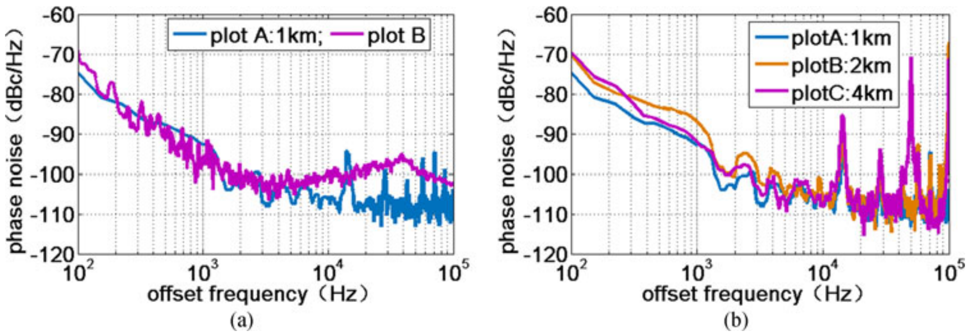

Fig. 4. The measured phase noise of 10 GHz microwave signal. (a) measured by proposed system (plot A) and measured by a commercial spectrum analyzer (plot B). (b) measured by proposed system with different time delays 1 km (plot A), 2 km (plot B), 4 km (plot C).

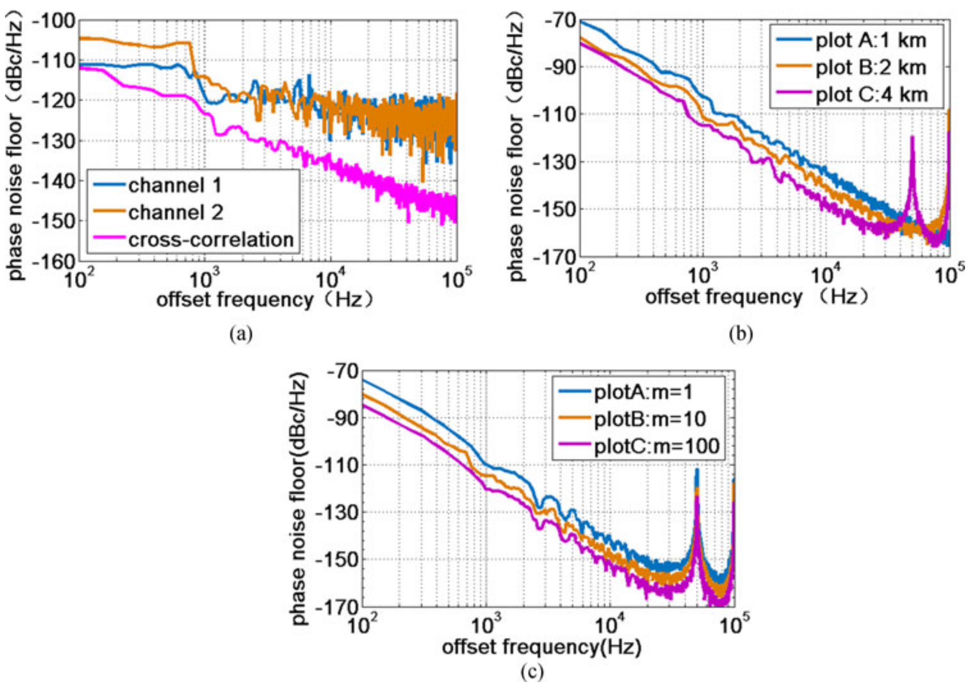

Fig. 5. Phase noise floor of the proposed phase noise measurement. (a) the cross correlation improves noise floor over single channel measurements. (b) with different time delays 1 km (plot A), 2 km (plot B), 4 km (plot C). (c) the cross-correlation spectrum obtained by averaging m = 1 (plot A), 10 (plot B), 100 (plot C) times.

Fig. 5 shows the measured phase noise floor of the phase noise measurement system when the microwave signal under test has a frequency of 10 GHz. To do this, an optical attenuator which has same attention as long fiber is used to replace the long delay-line fiber, which has been described in [23]. Fig. 5(a) shows the measured phase noise floor in each channel and their cross-correlation power spectrum. It indicates that the noise added by two channels, especially the noise of the amplifiers, has been removed. And Fig. 5(b) shows the phase noise floor of the measurement system when the long delay-line fibers have different lengths, clearly, the longer delay-line fiber used, the higher sensitivity can be achieved with the sacrifice of the measurement range, because a longer delay-line fiber leads the singularities appear at a lower frequency, which can be explained by Eq. (4). For the 1 km, 2 km and 4 km delay-line fibers, the measurement limits are about 30, 80, 180 kHz offset from the carrier, respectively. Fig. 5(c) shows the cross-correlation power spectrums at different averaging m = 1, 10, 100 times when the length of delay-line fiber is 4 km. Reductions of

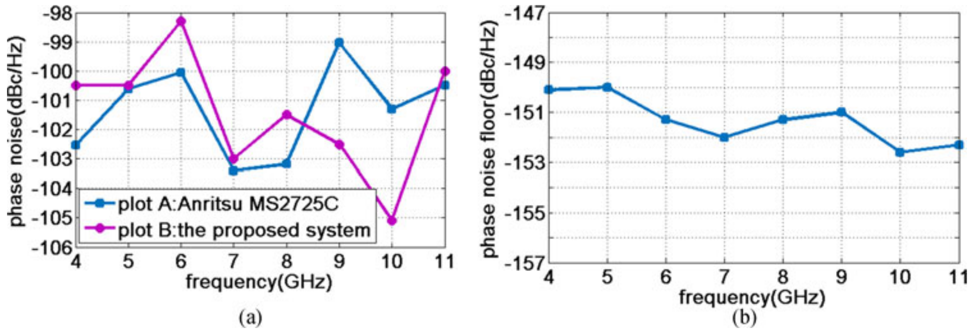

Fig. 6. (a) phase noise of a commercial microwave signal generator (Anritsu MG3693C) measured by the proposed system and a commercial spectrum analyzer (Anritsu MS2725C). (b) phase noise floor of the proposed system at 10 kHz offset in the frequency range from 4 to 11 GHz.

5 dB, 10 dB are obtained by averaging m = 10, 100 times, respectively, resulting in −147.6 dBc/Hz and −152.6 dBc/Hz measurement noise floors at 10 kHz offset frequency for 20 μs delay, severally. It agrees well with the described in Eq. (9) and Eq. (11).

To verify the advantage wide operation bandwidth of the proposed phase noise measurement system, the phase noise of a commercial microwave generator (Anritsu MG3693C) is tested by the proposed measurement system and a commercial spectrum analyzer (Anritsu MS2725C). Fig. 6(a) shows the measured phase noise at 10 kHz offset of the microwave generator when it changes from 4 GHz to 11 GHz. It can be concluded that the difference between the measured results of the two measurement systems are kept within 4 dB. In this verification experiment, the bandwidth of the MZM and the PDs limit the measurement range. Furthermore, the phase noise floors at a frequency range from 4 to 11 GHz in a 4-km fiber delay phase noise system at 10 kHz offset are measured as shown in Fig. 6(b). It shows that the fluctuation of the phase noise floors is less than 3 dB. The measured results in Fig. 6 confirm the measurement system can work effectively in a large range and has constant sensitivity over the full measurement range.

4. Conclusion

We proposed and realized a dual photonic-delay line cross correlation method based on DWDM for measuring the phase noise of microwave signals. With use of DWDM, the low loss kilometer-long optical fiber as photonic delay line is used together by the two channels, which makes it easier to control the kilometer-long fibers of the two channels are same. Furthermore, it reduces the use of several kilometers of fiber and a MZM, which reduce the cost of the system. And the use of VOLDs further broadens operation bandwidth of the proposed system. In addition, a lower phase noise floor has been obtained by more averaging of the cross-correlation spectrum. In the experiment, the phase noise of a 10-GHz microwave signal has been measured accurately. And the phase noise floor reaches −152.6 dBc/Hz at 10 kHz offset in a 20 μs delay measurement system by averaging m = 100 times. Besides, a large operation bandwidth of the proposed phase noise measurement system in the frequency range from 4 GHz to 11 GHz has been demonstrated, where the phase noise floor is nearly independent of frequency.

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