Digital Phase Noise Cancellation for a Coherent-Detection Microwave Photonic Link

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***Abstract*— An intensity-modulation and coherent-detection (IM/CD) microwave photonic (MWP) link with digital signal processing (DSP)-based phase noise cancellation is proposed and experimentally demonstrated. At the transmitter, the optical carrier is intensity-modulated by a radio-frequency (RF) signal and sent to a coherent receiver over a single-mode fiber (SMF). At the receiver, the intensity-modulated optical signal is coherently detected using a local oscillator (LO) laser source. The phase noise introduced by both the transmitter laser source and the LO laser source is converted into an amplitude noise at the output of the coherent receiver, which would be added to the in-phase component and quadrature component from the coherent receiver. The noise can be completely cancelled by summing the squared magnitudes of the in-phase and quadrature components from the coherent receiver, which can be implemented using a DSP unit. Error-free transmission of a 1.25-Gb/s quadrature phase shift keying modulated RF signal with a center frequency of 1.6 GHz over 25-km SMF is experimentally demonstrated. For a signal with a bit rate of 834 Mb/s, the receiver sensitivity can reach −24.5 dBm which is 20 dB better than that based on an intensity-modulation and direct-detection MWP link.**

***Index Terms*— Digital signal processing (DSP), laser phase noise, microwave photonic link, optical coherent detection, phase noise cancellation (PNC).**

I. INTRODUCTION

MICROWAVE photonic (MWP) links have been widely employed for applications such as antenna remoting, cable television, and wireless networking [1]–[3] and have been extensively studied. Numerous techniques have been proposed to improve the performance of an MWP link. Intensity modulation and coherent detection (IM/CD) is considered one of the very promising techniques to improve the performance of an MWP link, such as a superior receiver sensitivity compared with a conventional intensity-modulation and direct-detection (IM/DD) MWP link [4], [5]. Due to its high receiver sensitivity, the optical power through the whole optical link can be controlled low. As a result, the optical link becomes less sensitive to a variety of nonlinear effects. In addition, optical amplifiers for an IM/CD MWP link may not be needed. Thus, the amplified spontaneous emission (ASE) noise from the optical amplifiers, which occupies a wide bandwidth and is hard to remove, can be avoided. Furthermore, for dense wavelength-division multiplexing (DWDM) systems, channel selection can be easily realized by using electrical filters in a coherent receiver [1]–[3].

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On the other hand, an IM/CD MWP link suffers from the performance degradation due to the phase noise introduced from both the transmitter and LO laser sources. A few solutions have been proposed in recent years, such as the use of an optical phase-locked loop to lock the phase of the LO laser source [6], [7], the use of a very narrow linewidth laser source [8], [9], a dual-mode local light source [10], [11], or a phase noise canceling (PNC) circuit [12]–[14]. Although the use of an optical phase-locked loop provides optimal performance of an IM/CD MWP link, it makes the implementation very complicated. The use of a very narrow linewidth laser or a dual-mode local light source may not increase the complexity, but it will greatly increase the system cost. The use of a PNC circuit can cancel the phase noise, but the LO laser source has to operate with an offset wavelength from the transmitter laser source by an intermediate frequency (IF) that is two to three times higher than the bandwidth of the RF input signal. Therefore, an automatic frequency control (AFC) loop or a tunable laser source (TLS) has to be used to guarantee that the frequency difference between the transmitter laser source and the LO laser source is two or three times higher than the bandwidth of the RF input signal. In addition, since the PNC circuit utilizes the square law detection to cancel the phase noise, the circuit also generates the second order harmonics of the RF input signal, therefore, large amounts of energy will be wasted and large bandwidth RF signal transmission may not be possible.

In this letter, we theoretically study and experimentally evaluate a digital signal processing (DSP) assisted MWP link based on IM/CD for the transmission of a radio-frequency (RF) signal. The phase noise which is introduced by both the transmitter and LO laser sources can be, in principle, completely eliminated by summing the squared magnitudes of the in-phase and quadrature (I&Q) components from the coherent receiver. Compared with the conventional PNC circuits reported in [12]–[14], the primary advantages of this method include: 1) A DSP-based PNC module is easier to realize. 2) A DSP-based PNC module is much more accurate. For instance, it can avoid the performance reductions due to the unmatched path delay which may happen in a MWP link using an analog PNC circuit, as discussed in [14]. In addition, since no analog circuit is used, any signal distortion caused by the nonlinearity of an analog PNC circuit can be avoided. 3) A DSP-based PNC module does not need any AFC loop or phase locked loop. 4) A DSP-assisted MWP link can support both optical heterodyne detection and optical homodyne

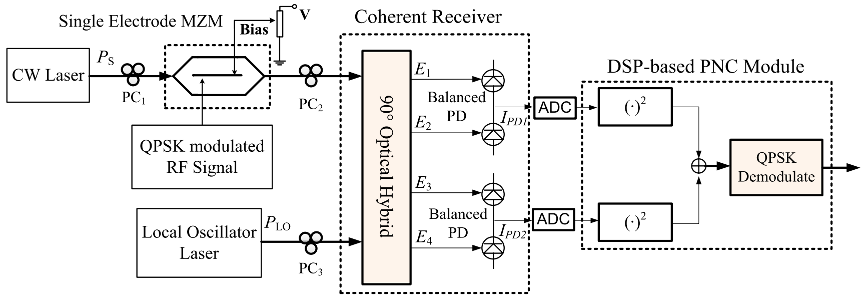

Fig. 1. Schematic diagram of the proposed IM/CD MWP link with a DSP-based PNC module. ADC: analog-to-digital converter. PC: polarization controller. CW laser: continuous-wave laser. Balanced PD: balanced photodetector. MZM: Mach-Zehnder modulator. QPSK: quadrature phase shift keying.

detection. The proposed DSP-assisted IM/CD MWP link is studied theoretically and verified by an experiment. The transmission of a 1.25-Gbps RF signal with a center frequency of 1.6 GHz over 25-km SMF is achieved. The phase noise terms from both the transmitter laser source and the LO laser source are cancelled successfully by the DSP-based PNC module. For a RF signal with a bit rate of 834 Mbps, the receiver sensitivity can reach −24.5 dBm which is 20 dB better than that based on an IM/DD MWP link.

II. Principle of Operation

Fig. 1 shows the schematic of the proposed DSP-assisted IM/CD MWP link. An RF signal is directly modulated on an optical carrier at a chirp-free single-electrode Mach-Zehnder modulator (MZM). A phase-diversity coherent optical receiver is used to detect the intensity-modulated optical signal from the transmitter. At the outputs of the phase-diversity coherent optical receiver, two channels of signals corresponding to the in-phase and quadrature (I&Q) components are obtained, which are then sent to the DSP-based PNC module. By summing the squared magnitudes of the I and Q components, the phase noise is completely cancelled.

When the MZM is biased at the quadrature point, the optical field at the output of the MZM is given by

$$E_s(t) = \sqrt{2P_s L_s}\cos\left(\pi x(t)/2V_\pi + \pi/4\right) e^{j(\omega_c t+\varphi_c(t))} \quad (1)$$

where P_s is the optical output power of the light wave from the transmitter laser source, ω_c is the angular frequency of the light wave, $x(t)$ is the RF input signal, $\varphi_c(t)$ is the phase term of the transmitter laser source, V_π is the half-wave voltage of the MZM, and L_s is the link loss between the coherent receiver and the transmitter. Similarly, the optical field at the output of the LO laser source can be written as

$$E_{LO}(t) = \sqrt{2P_{LO}} e^{j(\omega_{LO} t+\varphi_{LO}(t))} \quad (2)$$

where P_{LO} is the optical power of the light wave from the LO laser source, $\varphi_{LO}(t)$ is the phase term, and ω_{LO} is the angular frequency.

The optical signal from the transmitter and the light wave from the LO laser source are co-polarized and are applied to a 90° optical hybrid. At the four outputs of the 90° optical hybrid, we have four optical fields given by

$$E_1 = \sqrt{L}(E_s + E_{LO}) \quad (3)$$
$$E_2 = \sqrt{L}(E_s - E_{LO}) \quad (4)$$
$$E_3 = \sqrt{L}(E_s + E_{LO}e^{j\pi/2}) \quad (5)$$
$$E_4 = \sqrt{L}(E_s - E_{LO}e^{j\pi/2}) \quad (6)$$

where L is the link loss caused by the 90° optical hybrid.

By applying E_1 and E_2, and E_3 and E_4 to two balanced photodetectors, we have two output photocurrents given by

$$I_{PD1} = 4RL\sqrt{P_s P_{LO} L_s}\left[\cos\left(\pi x(t)/2V_\pi + \pi/4\right) \times \cos\left((\Delta\omega)t + \varphi(t)\right)\right] \quad (7)$$
$$I_{PD2} = 4RL\sqrt{P_s P_{LO} L_s}\left[\cos\left(\pi x(t)/2V_\pi + \pi/4\right) \times \sin\left((\Delta\omega)t + \varphi(t)\right)\right] \quad (8)$$

where $\Delta\omega$ is the frequency difference between the transmitter laser source and the LO laser source, $\Delta\omega = \omega_c - \omega_{LO}$, $\varphi(t)$ is the phase noise introduced by both the transmitter laser source and the LO laser source, $\varphi(t) = \varphi_c(t) - \varphi_{LO}(t)$. Then, the two signals, I_{PD1} and I_{PD2}, are separately sampled and digitized by two ADCs. Using the DSP, we can easily obtain

$$I_o^2 = I_{PD1}^2 + I_{PD2}^2 = 8R^2L^2P_sP_{LO}L_s\left(1 - \sin\left(\pi x(t)/V_\pi\right)\right) \approx 8R^2L^2P_sP_{LO}L_s\left(1 - \left(\pi x(t)/V_\pi\right)\right) \quad (9)$$

As can be seen, the RF signal is recovered, and it is independent of the phase noise.

When the MZM is biased at the null point, the optical field at the output of the MZM is given by

$$E_s(t) = \sqrt{2P_s L_s}\cos\left(\pi x(t)/2V_\pi + \pi/2\right) e^{j(\omega_c t+\varphi_c(t))} \quad (10)$$

The two output photocurrents, I_{PD1} and I_{PD2}, are rewritten as

$$I_{PD1} = -4RL\sqrt{P_s P_{LO} L_s}\left[\sin\left(\pi x(t)/2V_\pi\right) \times \cos\left((\Delta\omega)t + \varphi(t)\right)\right] \quad (11)$$
$$I_{PD2} = -4RL\sqrt{P_s P_{LO} L_s}\left[\sin\left(\pi x(t)/2V_\pi\right) \times \sin\left((\Delta\omega)t + \varphi(t)\right)\right] \quad (12)$$

Again, when doing the same operation at the DSP-based PNC module, we have,

$$I_o^2 = I_{PD1}^2 + I_{PD2}^2 = 8R^2L^2P_sP_{LO}L_s\left(1 - \cos\left(\pi x(t)/V_\pi\right)\right) \quad (13)$$

Again, I_o^2 is independent of the phase noise. If the input RF signal is an ASK-modulated RF signal, by applying the

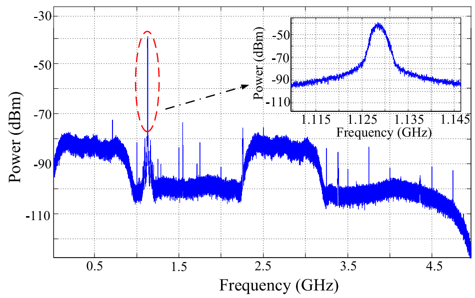

Fig. 2. Spectrum of the signal at the output of the coherent receiver (in-phase component).

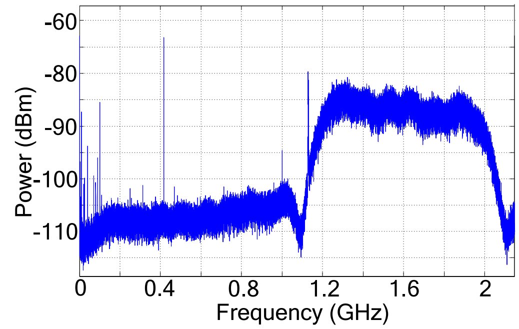

Fig. 3. Spectrum of the recovered RF signal at the output of the DSP-based PNC module.

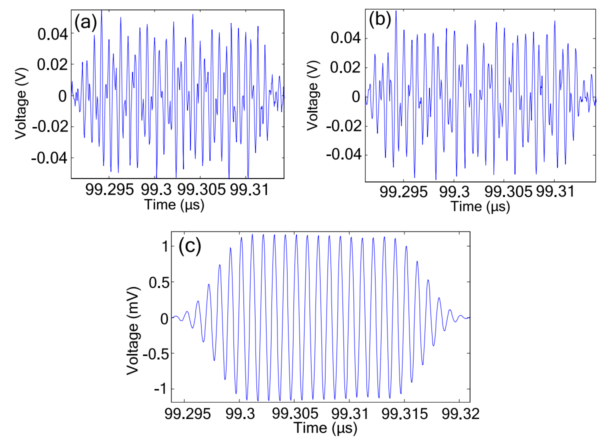

Fig. 4. Temporal waveform when the RF input signal is an ASK modulated RF signal with a center frequency of 500 MHz. (a) The in-phase component from the coherent receiver, (b) the quadrature component from the coherent receiver, and (c) the signal at the output of the DSP-based PNC module.

Bessel expansion to (13), we will obtain an ASK-modulated RF signal that is frequency doubled as compared with that of the input ASK-modulated RF signal.

III. Experiment

To verify that the proposed DSP-assisted IM/CD MWP link is effective in phase noise cancellation, an experiment is conducted based on the setup shown in Fig. 1. An optical wave at 1544.798 nm from a TLS (Anritsu MG9638A) is sent to the single-electrode MZM (JDSU) via a polarization controller (PC_1). The MZM has a bandwidth of 10 GHz and a half-wave voltage of about 5 V. The linewidth and output power of the light wave from the TLS is 700 KHz and 7.8 dBm, respectively. A QPSK-modulated RF signal generated by an arbitrary waveform generator (Tektronix AWG7102) is applied to the MZM via the RF port. The MZM is biased at the quadrature point. Then, the optical signal from the output of the MZM, which is intensity modulated by the RF signal, is sent to the coherent receiver (Discovery Semiconductors DP-QPSK 40/100 Gbps Coherent Receiver Lab Buddy) via PC_2. A second TLS (Yokogawa AQ2201) with a linewidth of about 1 MHz at a wavelength of 1544.788 nm and an optical power of 9 dBm is used as the LO laser source. The wavelength difference between the transmitter laser source and the LO laser source is 0.01 nm, corresponding to beat frequency of about 1.25 GHz. The light wave from the LO laser source is sent to the coherent receiver through PC_3 via the LO port. A Digital Storage Oscilloscope (Agilent DSO-X 93204A) is employed to perform the ADC with a sampling rate of 10 GSa/s. The sampled signals (in-phase and quadrature components, I_{PD1} and I_{PD2}) are processed off-line in a computer.

Note that the lengths of the two paths for the in-phase and the quadrature components should be precisely matched. To evaluate the length difference, we apply an electrical pulse from an AWG to the MZM and measure the output pulses from the two output ports of the coherent receiver. The two electrical pulses from the coherent receiver are monitored by a DSO. By comparing the rising edges of the two pulses we find that the delay between the two pulses is less than 0.5×10^{-10}s. Thus, the two paths in the coherent receiver are well matched.

Then, we apply a QPSK-modulated RF signal to the MZM. The QPSK-modulated RF signal has a center frequency of 1.6 GHz and a symbol rate of 417 MSymbol/s. Fig. 2 shows the spectrum of the QPSK-modulated RF signal from the coherent receiver (in-phase component). It is seen that the RF signal is up converted to 2.85 GHz because of the wavelength difference of about 0.01 nm corresponding to a frequency of 1.25 GHz. The RF carrier in Fig. 2 is noisy, which is caused by the phase noise from the transmitter laser source and LO laser source. After processing at the DSP-based PNC module, the RF QPSK-modulated signal is down converted to its original frequency of 1.6 GHz. Apparently, the DSP-based PNC module can also act as a frequency down-converter. Fig. 3 shows the spectrum of the RF signal at the output of the DSP-based PNC module.

Fig. 4(a) and (b) shows the temporal waveforms of the in-phase component and the quadrature component from the coherent receiver within one symbol time period, when the MZM is biased at the null point and an ASK modulated RF signal is applied to the MZM. Fig. 4(c) shows the temporal waveform at the output of the DSP-based PNC module. For this measurement, the center frequency of the input RF signal is controlled to be 500 MHz.

It can be seen that the envelopes of the signals in Fig. 4(a) and (b) are not constant. The effectiveness of the DSP-based PNC module is apparently seen from the waveform shown in Fig. 4(c), where the amplitude is constant, and the phase noise is fully cancelled. The center frequency of the ASK modulated RF signal after the DSP-based PNC is doubled, which is 1 GHz.

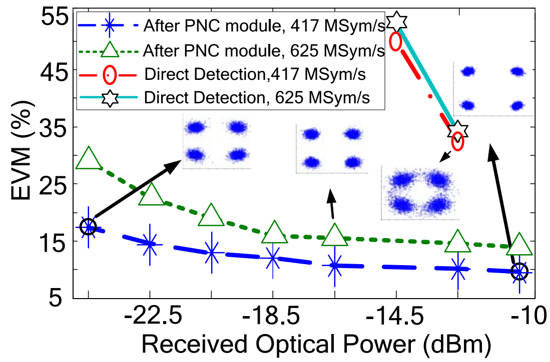

Fig. 5. Comparison of the EVMs for the transmission of a QPSK-modulated RF signal with a center frequency of 1.6 GHz over 25 km SMF based on coherent detection using the DSP-based PNC and based on direct detection.

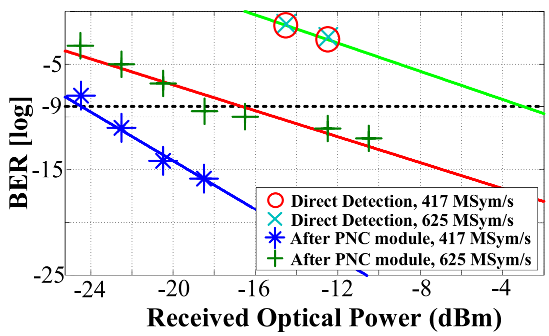

Fig. 6. The estimated BER for the transmission of a QPSK modulated RF signal with a center frequency of 1.6 GHz over 25 km SMF based on coherent detection using the DSP-based PNC and based on direct detection.

To further study the performance of the proposed DSP-assisted IM/CD MWP link, we also measure the error vector magnitude (EVM) versus the received optical power, which is compared with that of a conventional IM/DD MWP link. The conventional IM/DD MWP link consists of a laser source, a chirp-free MZM which is biased at the quadrature point, a 25-km SMF and a PD.

Fig. 5 shows the measured EVM as a function of the received optical power for the transmission of a QPSK-modulated RF signal at 417 MSymbol/s, 625 MSymbol/s over a 25-km SMF with coherent detection using the DSP-based PNC module and direct detection. The center frequency of the QPSK-modulated RF signal is 1.6 GHz. Then, the bit error rate (BER) is estimated based on the measured EVM by using the relationship between the EVM and the BER [15]. Fig. 6 shows the corresponding estimated BER as a function of the received optical power. It can be seen that the receiver sensitivity for the transmission of the 417 MSymbol/s QPSK-modulated RF signal with the coherent detection using the DSP-based PNC module can reach -24.5 dBm, which is lower than that of the direct detection by more than 20 dB. Here, the receiver sensitivity is defined as the minimum average received optical power required to achieve a fixed BER of 10^{-9}. The corresponding constellation for the 417 MSymbol/s QPSK modulated RF signal with the coherent detection, when the received optical power is -24.5 dBm, is shown in Fig. 5, which is very clear. The receiver sensitivity for the transmission of the 625 MSymbol/s QPSK modulated RF signal with the coherent detection using the DSP-based PNC module is also measured, which is about -20 dBm.

IV. Conclusion

A DSP-assisted IM/CD MWP link was proposed and experimentally demonstrated. The fundamental concept of the approach to phase noise cancellation was to sum the squared magnitudes of the in-phase and quadrature components from the coherent receiver by using a DSP-based PNC module. The phase noise terms from both the transmitter laser source and the LO laser source were completely cancelled. The effectiveness of the proposed technique for noise cancellation was verified by an experiment. Error-free transmission of a 1.25-Gbps RF signal with a center frequency of 1.6 GHz over 25 km SMF was achieved. The main advantages of the DSP-based PNC technique include:

- It can support both optical heterodyne detection and optical homodyne detection.
- It does not need any complicated AFC loop or phase locked loop.
- Signal distortion caused by the nonlinearity of an analog PNC circuit is avoided.

For a signal with a bit rate of 834 Mbps, the receiver sensitivity was -24.5 dBm. Compared with a conventional IM/DD MWP link, the receiver sensitivity of the proposed MWP link was improved by more than 20 dB.

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