A Phase-Modulated Microwave Photonic Link With an Extended Transmission Distance

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***Abstract*— A novel technique to transport a microwave signal over an optical fiber based on phase-modulation and coherent in-phase (I) and quadrature-phase (Q) demodulation with an extended transmission distance is proposed and experimentally demonstrated. In the transmitter, a Sagnac loop incorporating a phase modulator (PM) is used to generate two orthogonally polarized optical signals with one being phase modulated and the other with no modulation that acts as a remote optical reference signal. The orthogonally polarized optical signals are transmitted over a single-mode fiber (SMF) to a polarization and phase diversity coherent receiver, and are coherently detected with a free-running optical local oscillator at the receiver. Since the phase-modulated and the reference signals are transmitted over the same SMF, the optical phases are correlated, and the original signal can be recovered based on a digital signal processing algorithm. The proposed technique is experimentally evaluated. Compared with a phase-modulated coherent I/Q demodulated link without using an optical phase correlated reference signal, the transmission distance is extended from 50 m to 10 km, while providing a link gain and a spurious-free dynamic range (SFDR) of −9.5 dB and 115.8 dB$\cdot$Hz$^{2/3}$, respectively.**

***Index Terms*— Microwave photonics, phase modulation, coherent detection, analog photonic link.**

I. Introduction

DUE to the inherent advantages of low transmission loss and broad bandwidth offered by modern photonics, the transmission of analog signals over a fiber link, also called an analog photonic link (APL), has been considered an effective solution for transmission of broadband microwave signals. The key limitations of an APL are the relatively low dynamic range and the insufficient link gain [1]. For an APL based on intensity-modulation direct-detection (IM/DD) using a Mach Zehnder modulator (MZM) and a photodetector (PD), the dynamic range is limited mainly by the inherent nonlinearity of the MZM. The link gain is limited mainly by the low power handling capability of the PD. In addition, the low electrical-to-optical conversion efficiency of the MZM is another factor that also limits the link gain. One solution to increase the dynamic range and the link gain is to use phase modulation and coherent detection (PM/CD) [2]–[5]. Compared with an IM/DD link, a coherent detection link can have a gain that is 20 dB higher [6] and an increased SFDR. To implement a PM/CD APL, an optical local oscillator (OLO) at the coherent receiver is needed. A few techniques to implement coherent detection have been proposed. A simple technique is to use a free running OLO [7]. However, a free-running OLO has a phase that is not correlated with that of the optical carrier from the transmitter, thus the mixing of the optical signal with the OLO source will deteriorate the link performance. To generate an OLO source that is phase correlated with the transmitter optical carrier, one may use an optical phase locked loop (OPLL) [8] to lock the phase of the OLO source with that of the transmitter optical carrier. The major limitation of using an OPLL is the relatively small bandwidth, thus an OLO source with a narrow linewidth has to be used. To implement an APL with a high dynamic range and a large link gain, another solution is to use phase-modulation and coherent I/Q demodulation [3], [4], in which both the I and Q components at the outputs of the coherent receiver are used to form a complex quantity, which is used to extract the microwave signal based on a digital signal processing (DSP) algorithm. Coherent I/Q demodulation provides an ideal approach to demodulating a phase-modulated microwave signal. Again, similar to any coherent detection technique, a coherent OLO source is needed. In [3] and [4], the light wave of the OLO source is generated by tapping part of the light wave from the transmitter light source and sent to the coherent receiver via a second optical fiber. To eliminate the optical path mismatch, which can be seen as a phase noise, a feedback control loop with a fiber stretcher is needed, which is effective only for a short distance link [4].

In this letter, we propose a novel phase-modulation and coherent I/Q demodulation APL without using a second fiber link to deliver the OLO source to the receiver. Instead, a remote optical reference signal is generated at the transmitter and sent to the receiver by sharing the same optical fiber through polarization multiplexing. In the transmitter, a linearly polarized light wave is split by a polarization beam splitter (PBS) and sent to a Sagnac loop in which a PM is incorporated to generate two orthogonally polarized optical signals with one being phase modulated and the other with no modulation due to the traveling-wave nature of the PM [9].

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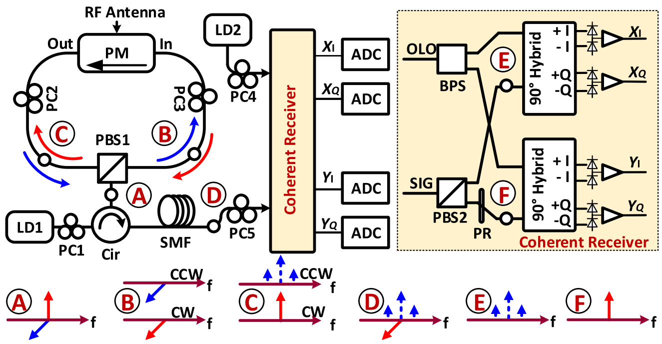

Fig. 1. The proposed phase-modulated and coherent-I/Q demodulation APL. LD, laser diode; Cir, circulator; PBS, polarization beam splitter; PM, phase modulator; PC, polarization controller; BPS, beam power splitter; PR, polarization rotator; DSP, digital signal processor; SIG, signal; OLO, optical local oscillator. Inset: The architecture of the polarization and phase diversity coherent receiver.

The light wave with no modulation is used to as a remote optical reference signal. At the output of the Sagnac loop, the phase-modulated signal and the unmodulated optical wave are polarization multiplexed and sent to the coherent receiver via a single fiber link. After transmission, the optical signals are applied to a polarization and phase diversity coherent receiver (PPDCR). In the receiver, the optical fields of the phase-modulated signal and the orthogonally polarized reference signal are coherently I/Q detected where a free-running OLO is used. By using a DSP algorithm, the input microwave signal can be recovered from the detected two optical fields. The proposed APL is experimentally demonstrated. An extended transmission distance of 10 km is demonstrated of which a link gain of −9.5 dB and a spurious-free dynamic range (SFDR) of 115.8 dB·Hz$^{2/3}$ are achieved.

II. Principle

Fig. 1 shows the schematic of the proposed APL. It consists of a transmitter, an SMF, and a PPDCR (shown in the inset of Fig. 1). In the transmitter, a linearly polarized light wave from a laser diode (LD1) is sent through a polarization controller (PC1) to a Sagnac loop via a PBS, and is decomposed to two orthogonally polarized light waves. A PM and two PCs (PC2 and PC3) are incorporated in the Sagnac loop. Since the PM is a traveling-wave device, when the light wave and the modulation signal are traveling along the same direction, the light wave is effectively modulated. On the other hand, if the light wave and the modulation signal are traveling along the opposite directions, due to the velocity mismatch, the modulation is very weak and can be neglected [9]. In the analysis, we take the two orthogonal directions of the PBS (PBS1) in the Sagnac loop as the reference directions (horizontal and vertical) of the system. As shown in Fig. 1, the principle axis of the PM is aligned to have an angle of 45° relative to the two reference directions, and both PC2 and PC3 would introduce a 45° rotation of the polarization to the bi-directionally transmitted light waves. As the oppositely transmitted two light waves are traveling in the same optical path, the light waves, which are polarization multiplexed at the output of the Sagnac loop, are phase correlated. Then, the polarization-multiplexed light waves are sent to the PPDCR over the SMF. A light wave from the OLO is sent to the PPDCR via a 4$^{\text{th}}$ PC (PC4). The polarization directions of the polarization-multiplexed light waves are aligned with the reference directions by tuning a 5$^{\text{th}}$ PC (PC5). Assuming β is the angle between the polarization of the light wave from the OLO and the horizontal direction, the signals at the outputs of the coherent receiver can be expressed as

$$X_I(t) = \frac{\sqrt{2}}{2} R\sqrt{P_S P_{\mathrm{LO}}}\cos\alpha\cos\beta\cos\left[\omega_{\mathrm{IF}}t + \varphi_{\mathrm{sig}}(t) + \Delta\varphi_{\mathrm{LO}}(t)\right] \tag{1}$$

$$X_Q(t) = \frac{\sqrt{2}}{2} R\sqrt{P_S P_{\mathrm{LO}}}\cos\alpha\cos\beta\sin\left[\omega_{\mathrm{IF}}t + \varphi_{\mathrm{sig}}(t) + \Delta\varphi_{\mathrm{LO}}(t)\right] \tag{2}$$

$$Y_I(t) = \frac{\sqrt{2}}{2} R\sqrt{P_S P_{\mathrm{LO}}}\sin\alpha\cos\beta\cos\left[\omega_{\mathrm{IF}}t + \Delta\varphi_0 + \Delta\varphi_{\mathrm{LO}}(t)\right] \tag{3}$$

$$Y_Q(t) = \frac{\sqrt{2}}{2} R\sqrt{P_S P_{\mathrm{LO}}}\sin\alpha\cos\beta\sin\left[\omega_{\mathrm{IF}}t + \Delta\varphi_0 + \Delta\varphi_{\mathrm{LO}}(t)\right] \tag{4}$$

where ω_{IF} is the intermediate frequency (IF) corresponding to the wavelength difference between the optical signal from the transmitter and the OLO, P_S is the power of the light emitted from LD1 of the transmitter, P_{LO} is the OLO power, R is the responsitivity of the PD, α is the angle between the polarization of the light wave from LD1 and the horizontal reference direction, Y_{I} and Y_{Q} are the detected signals at the outputs of the PPDCR corresponding to the remote optical reference signal with its spectrum shown in red at the bottom of Fig. 1, X_{I} and X_{Q} are the detected signals at the outputs of the PPDCR corresponding to the phase-modulated signal with its spectrum shown in blue line at the bottom of Fig. 1, $\Delta\varphi_{\mathrm{LO}(t)}$ is the phase difference between the phase-modulated signal and the OLO, $\Delta\varphi_0$ is the phase difference between the phase-modulated signal and the remote optical reference signal, and $\varphi_{\mathrm{sig}}(t) = \frac{\pi V_{\mathrm{sig}}(t)}{V_\pi}$ is the optical phase generated by the microwave modulation signal at the PM, where V_π is the half-wave voltage of the PM. In the implementation, the polarization direction of the light wave from the OLO and the remote optical reference signal are tuned to have the same polarization direction, say, the horizontal direction. Thus, β is zero.

The signals at the outputs of both the I and Q channels are used to form two complex quantities $K_X \equiv X_I(t) + jX_Q(t)$ and $K_Y \equiv Y_I(t) + jY_Q(t)$ [3], [4], and these quantities are expressed as

$$K_X = \frac{\sqrt{2}}{2} R\sqrt{P_S P_{\mathrm{LO}}}\cos\alpha\cos\beta\exp\left\{j\left[\omega_{\mathrm{IF}}t + \varphi_{\mathrm{sig}}(t) + \Delta\varphi_{\mathrm{LO}}(t)\right]\right\} \tag{5}$$

$$K_Y = \frac{\sqrt{2}}{2} R\sqrt{P_S P_{\mathrm{LO}}}\sin\alpha\cos\beta\exp\left\{j\left[\omega_{\mathrm{IF}}t + \Delta\varphi_0 + \Delta\varphi_{\mathrm{LO}}(t)\right]\right\} \tag{6}$$

and ω_{IF} and $\Delta\varphi_{\mathrm{LO}(t)}$ can be cancelled by performing

$$\frac{K_X}{K_Y} = \mathrm{ctg}\alpha \times \exp\left\{j\left[\varphi_{\mathrm{sig}}(t) - \Delta\varphi_0\right]\right\}. \tag{7}$$

As the reference and phase-modulated signals are traveling in the same optical path, the relative phase variations between the two optical signals due to environmental disturbances are very small, thus $\Delta\varphi_0$ could be considered as a static phase. When $\Delta\varphi_0 = 0$, considering that $\mathrm{ctg}\alpha = 1$, the microwave modulation signal $V_{\mathrm{sig}(t)}$ can be recovered,

$$\frac{\pi V_{\mathrm{sig}(t)}}{V_\pi} = \varphi_{\mathrm{sig}(t)} = Im\left[\ln\left(\frac{K_X}{K_Y}\right)\right] \tag{8}$$

From (8), we can see the phase-modulated input signal can be recovered by a DSP algorithm without any approximation.

III. Experimental Results

An experiment based on the setup shown in Fig. 1 is performed. A light wave at 1552.524 nm from an LD (Agilent N7714A) is sent through PC1 to the Sagnac loop. The light wave is decomposed into two orthogonally polarized light waves that are traveling along the counter-clockwise and clockwise directions. In the experiment, a microwave signal generated by a signal generator is applied to the PM. The PM is a traveling-wave device. For a light wave that is traveling along the same direction as the microwave modulation signal, the light wave is effectively modulated. On the other hand, if a light wave that is traveling along the opposite direction as the microwave modulation signal, the light wave is very weakly modulated due to velocity mismatch. As shown in Fig. 1, the counter-clockwise optical carrier is effectively modulated by the microwave signal at the PM (JDS-U, 20 GHz, $V_\pi = 7.8$ V), and the clockwise optical carrier is very weakly modulated. The optical signals at the output of the Sagnac loop are combined at the PBS and sent via an SMF to the PPDCR (Discovery Semiconductors DP-QPSK 40/100 Gbps Coherent Receiver Lab Buddy). To evaluate the data transmission performance, a 2.5-GHz 625 MSym/s QPSK signal generated by an arbitrary waveform generator (AWG, Tektronix AWG7102), amplified by an electronic amplifier (Picosecond Pulse Lab 5828), is applied to the PM. The light wave from the OLO is generated by a second LD (LD2) with a power of 9 dBm and a wavelength of 1552.444 nm, which is employed to coherently demodulate the orthogonally polarized signals at the PPDCR. The optical power at the input of the PPDCR is −9 dBm. The four signals at the outputs of the PPDCR are digitized by the four channels of a real-time oscilloscope (Agilent, DSO-X 93204A) with a sampling rate of 40 GSa/s for each channel. The microwave signal is recovered off-line in a computer based on (8).

In forming the complex quantities given in (5) and (6), the Gram-Schmidt orthogonalization procedure (GSOP) [10] is applied to X_{I} and X_{Q}, and Y_{I} and Y_{Q} to compensate for the amplitude mismatch and phase misalignment between the two orthogonal outputs of the PPDCR which are caused by imperfect characteristics of the receiver. The spectra of the Y_Q and X_Q, which are the spectra of the quadrature component corresponding to the reference and the phase-modulated signals, are shown in Fig. 2(a) and (b). As indicated, the polarization of the remote optical reference signal is aligned with the horizontal direction at the input of the PPDCR, as shown at point D in Fig. 1. If PC5 is

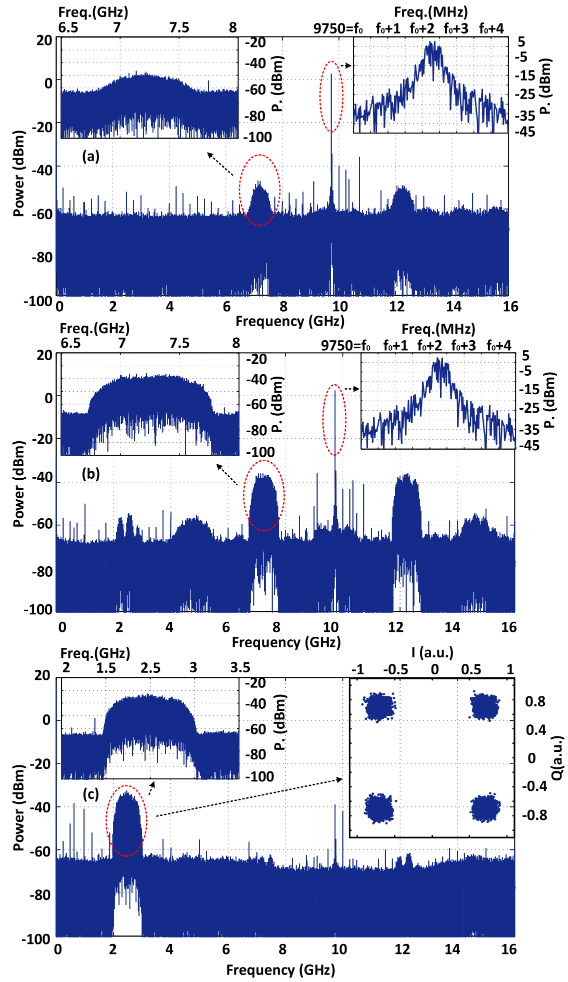

Fig. 2. The spectra of the signals at the output of the coherent receiver and the spectrum of the recovered signal. (a) The spectrum of the Y_Q, (b) the spectrum of the X_Q, and (c) the spectrum of the recovered signal.

properly adjusted, the phase-modulated optical signal will be fully suppressed at point F due to polarization orthogonality. Thus, at the output ports Y_{I} and Y_{Q} of the PPDCR, only an IF carrier is generated and no sidebands will be produced. Fig. 2(a) shows the IF carrier at the output port Y_{Q}. As can be seen an IF signal which is a beat signal between the optical signals from the transmitter and the light wave from the OLO is generated. Two sidebands are also observed, but are very weak. The imperfect cancellation of the sidebands is due to the poor extinction ratio of PBSs. Since the center frequency of the microwave signal is 2.5 GHz, we can see the sidebands are located ± 2.5 GHz apart from the 10-GHz IF carrier. The details of the sideband at 7.5 GHz at the PPDCR output port Y_Q, and the corresponding 10-GHz IF carrier are shown as two insets in Fig. 2(a).

Fig. 2(b) shows the spectrum of a 10-GHz IF signal obtained at the output port X_Q of the PPDCR. Two sidebands with greater powers are observed. The details of the sideband at 7.5 GHz at one PPDCR output port X_Q, and the corresponding IF carrier are shown as two insets in Fig. 2(b). The spectrum of the recovered signal is shown in Fig. 2(c), and the details of the spectrum and the constellation of the recovered signal are shown as two insets of in Fig. 2(c). Since the OLO is a free-running LD, and its phase is not locked to the phase of the optical carrier from the transmitter, the spectrum of the IF carrier is wide. By applying the DSP algorithm, the phase noise from the OLO is cancelled and the demodulated signal is free from the OLO phase noise, which is confirmed by the back-to-back (BTB) constellation diagram, where an EVM of 10.35% is obtained, as shown in Fig. 2(c). Note that the IF component in the demodulated signal is not fully canceled, as can be seen from Fig. 2(c). The imperfect cancellation of the IF is attributed to the mismatch of the travelling paths of X_Q, X_I, Y_Q, and Y_I. Since the frequency of the IF component is far from the frequency of the recovered microwave signal, it can be filtered out using a digital low-pass filter.

We then evaluate the link performance in terms of the link gain and the SFDR. We first do a two-tone test, in which two microwave signals at 6 GHz and 6.01 GHz are generated and applied to the PM. The optical power at the input of the coherent receiver is controlled to be −6 dBm and the power of the OLO laser is set at 6 dBm. The wavelengths of the optical sources at the transmitter and the OLO are 1552.524 nm and 1552.444 nm, respectively. We then increase the powers of the microwave input signals from 5 dBm to 14 dBm, and the output powers of the recovered microwave signals and the IMD3 are measured. Note that the powers of the two tones are maintained identical when increasing the input microwave powers. For comparison, the microwave input–output behaviors of an APL with a single coherent receiver (SCR) and an APL with IM/DD are also investigated. The SCR APL is implemented using a free-running OLO without phase noise cancellation and the performance is evaluated from the experimental data using either (1) or (2). The performance of the IM/DD APL is studied by simulation using the VPI TransmissionMaker, where the same link parameters, including the incident light power to the PD, the RF gain, and the Vπ of the modulator, are used.

The noise floor of the employed oscilloscope is −154.2 dBm/Hz for a V/div setting of 50 mV/div, thus the SFDR of the proposed APL for BTB transmission is calculated to be 118.2 dB·Hz$^{2/3}$, and the third-order intercept point (OIP3) is 23.1 dBm. With 10-km SMF transmission, the optical power at the input of the receiver is −8.5 dBm, the OIP3 is 19.3 dBm and the SFDR is 115.8 dB·Hz$^{2/3}$. The SFDRs of the SCR APL and the IM/DD APL for BTB transmission are 92.92 dB·Hz$^{2/3}$ and 99.79 dB·Hz$^{2/3}$, respectively, and those after 10-km transmission are 91.95 dB·Hz$^{2/3}$ and 96.11 dB·Hz$^{2/3}$, respectively. The link gain for the proposed APL for both BTB and 10-km transmission are also evaluated, which is done by calculating the ratio between the input and output powers of the microwave signals. The BTB and the 10-km link gains of the proposed APL are −8.9 dB and −9.5 dB, respectively. The OIP3s with and without transmission of the SCR and the IM/DD APLs are provided in Fig. 3. The BTB and10-km link gains of the SCR APL are −41.0 dB and −42.7 dB, respectively, and the BTB and the 10-km link gains of the IM/DD APL are −38.8 dB and −44.3 dB, respectively.

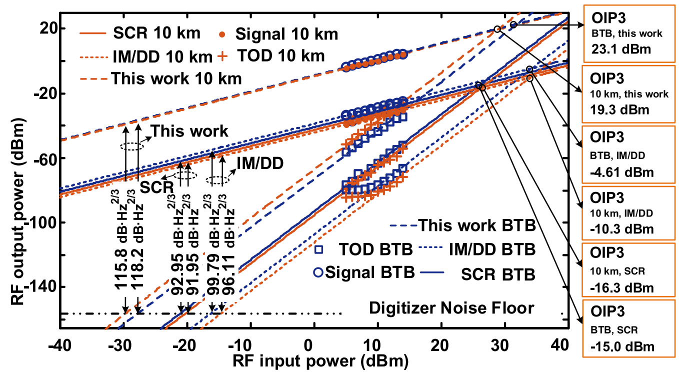

Fig. 3. The microwave input–output behaviours of the proposed APL, the SCR APL and the IM/DD APL.

IV. Conclusion

A new PM/CD APL with an extended transmission distance was proposed and experimentally demonstrated. The fundamental concept of increasing the transmission distance while maintaining a good link gain and SFDR was to use a reference signal, which was generated at the transmitter and transmitted to the coherent receiver over a same fiber with the optical signal based on polarization multiplexing, thus maintaining an identical phase relationship. By using of I/Q detection at the coherent receiver, and employing a DSP algorithm, the phase noise from the independent OLO laser source was cancelled and the original microwave signal was recovered. The proposed technique was experimentally evaluated. The performance in terms of SFDR and link gain of the proposed APL are better than the SCR and IM/DD APLs. Compared with a phase-modulated coherent I/Q demodulated link without using a phase-correlated reference signal, the transmission distance was extended from 50 m to 10 km, while providing a link gain and an SFDR of −9.5 dB and 115.8 dB·Hz$^{2/3}$, respectively.

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