Data Rate Quadrupled Coherent Microwave Photonic Link

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***Abstract*— A data rate quadrupled microwave photonic link (MPL) based on coherent detection and digital signal processing (DSP) is proposed and experimentally demonstrated. The data rate is quadrupled by employing both intensity and phase modulation and polarization multiplexing to transmit four microwave vector signals with an identical microwave center frequency over a single optical carrier. The recovery of the four microwave signals is implemented at a coherent receiver followed by DSP with a new algorithm, to separate the four microwave vector signals and to eliminate the phase noise from the transmitter and local oscillator laser sources and to cancel the unstable frequency offset between the two laser sources. Error-free transmission of four 2.5-Gpbs 16-QAM microwave vector signals with a total data rate of 10 Gbps if forward error correction (FEC) is employed. The total net data rate is 9.225 Gbps if the zero padding and the FEC (overhead 6.7%) are considered. The use of the proposed MPL for the implementation of 4 × 4 MIMO is also discussed.**

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

I. INTRODUCTION

TO MEET the requirements of the fifth generation wireless systems (5G), the transmission of multiple wireless signals over a single optical fiber enabling multi-input multi-output (MIMO) [1]–[3], a technique highly demanded for the 5G systems, are required. Numerous schemes have been proposed in recent years [1]–[6]. For example, one may transmit the digitized in-phase and quadrature components of a wireless signal in a binary sequence in the time domain over an optical fiber [2], [3]. However, the modulation format is ON-OFF-Keying, which makes the spectral efficiency low [3]. To increase the spectral efficiency, the transmission of multiple wireless signals based on frequency-division multiplexing (FDM) over a single wavelength is proposed [1]. One drawback of such a scheme is that electrical local oscillators (ELOs) with different frequencies for different wireless signals to realize frequency conversion are needed at a remote radio head (RRH), making the RRH complicated and costly. Recently, we proposed two schemes to implement a coherent microwave photonic link (MPL) enabling a centralized radio access network supporting the transmission of multiple wireless signals over a single wavelength, which has a key advantage of a simplified RRH. Since microwave frequency allocation and modulation are all performed at the central station [4]–[5], no ELOs are needed at the RRH, and thus the RRH is simplified. However, since one of the two polarization states is used for the transmission of a pilot tone, polarization multiplexing for the transmission of a second data channel cannot be employed. Thus, the total number of transmitted wireless signals are halved. To solve this problem, a coherent MPL using low-cost free-running laser sources with optical independent single-sideband and optical orthogonal modulation was proposed [6]. Since polarization multiplexing can be employed, the number of transmitted wireless signals is doubled. However, to separate the multiple signals, two pilot tones at different microwave frequencies have to be transmitted to the receiver which would decrease the energy efficiency. In addition, the center frequency of the transmitted wireless signals is not transparent to the MPL due to the need of two bandpass filters to eliminate the two pilot tones. For future optical-wireless systems, the center frequency and the data rate should be transparent to the optical link. Also, such a MPL is only suitable for downlink transmission, since digital signal processing (DSP) is needed in a RRH, making the RRH complicated and costly.

In this letter, we propose a novel MPL based on coherent detection and DSP, with a data rate that is quadrupled by employing both intensity and phase modulation and polarization multiplexing to transmit four microwave vector signals with an identical microwave center frequency over a single optical carrier. The number of the transmitted wireless signals is four times that of a regular intensity-modulation and coherent-detection MPL. Since no pilot tones are used, the center frequencies of the wireless signals and their data rates are transparent to the MPL.

At the transmitter, a light wave from a laser source is divided into two channels, and the light wave in each channel is phase modulated by a microwave vector signal and then intensity modulated by a second microwave vector signal. The two modulated optical signals from the two channels are polarization multiplexed at a polarization beam combiner (PBC) and transmitted over a single-mode fiber (SMF). At the receiver, coherent detection with a free-running local oscillator (LO) laser source is used to detect the two orthogonally polarized optical signals. After DSP, the four microwave vector signals are separated and the phase noise and the unstable frequency difference are cancelled. The proposed scheme is validated by an experiment. The transmission of four 2.5-Gbps 16 quadrature amplitude modulation (16-QAM) microwave signals with an identical center frequency of 2.5 GHz over 10-km SMF

Manuscript received February 3, 2017; revised March 28, 2017; accepted May 1, 2017. Date of publication May 3, 2017; date of current version June 13, 2017. This work was supported by the Natural Sciences and Engineering Research Council of Canada. *(Corresponding author: Jianping Yao.)*

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Digital Object Identifier 10.1109/LPT.2017.2700758

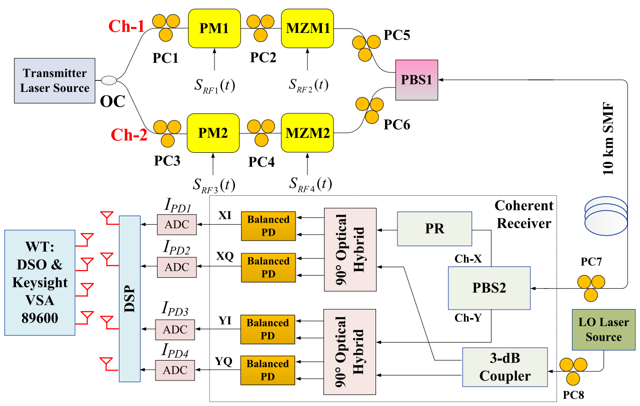

Fig. 1. Schematic of the proposed MPL. ADC: analog-to-digital converter, DSO: digital signal oscilloscope, PC: polarization controller, PD: photodetector, MZM: Mach-Zehnder modulator, DSP: digital signal processing, PBS: polarization beam splitter, PR: polarization rotator, PM: phase modulator, VSA: vector signal analyzer, WT: wireless terminal.

with a total data rate of 10 Gbps is experimentally demonstrated. The error vector magnitudes (EVMs) are measured to be 9.5%. If forward error correction (FEC) is employed, error-free transmission can be achieved. If the zero padding and FEC overhead (6.7%) are taken into account, the total net data rate is 9.225 Gbps. Since four wireless signals are simultaneously transmitted, the MPL is suitable for the implementation of 4 × 4 MIMO. In the experiment, limited by the number of channels of an arbitrary waveform generator (AWG) to generate the wireless signals, two orthogonal frequency division multiplexing (OFDM) signals are generated and transmitted, a 2×2 MIMO MPL is experimentally demonstrated. The total data rate is 0.9 Gbps. The EVMs for the two received wireless signals at the wireless terminal are measured to be 8.6%.

II. PRINCIPLE OF OPERATION

Fig. 1 shows the schematic diagram of the proposed DSP-assisted coherent MPL. At the transmitter, a light wave from a continuous-wave (CW) laser source is split into two channels (Ch-1 and Ch-2) by a 3-dB optical coupler (OC), with each of the light wave being firstly phase modulated by a 16-QAM microwave signal, and then intensity modulated by a second 16-QAM microwave signal. The modulated optical signals from the two channels are polarization multiplexed at a polarization beam splitter (PBS1), and transmitted to the receiver over a SMF. Since the four microwave signals have an identical center frequency, frequency-division multiplexing (FDM) in the microwave domain can be employed to incorporate more microwave channels to further increase the data rate of the MPL.

At the receiver, a coherent receiver with a free-running LO is used to coherently detect the two orthogonally polarized optical signals. The two optical signals are sent to a second PBS (PBS2), to separate the orthogonally polarized optical signals into two channels (Ch-X or Ch-1 and Ch-Y or Ch-2). Then, the two signals from the Ch-X and Ch-Y channels and an LO signal from an LO laser source are sent to two optical hybrids and detected by four balanced photodetectors (PDs). At the output of the coherent receiver, four electrical signals, I_{PD1} and I_{PD2} from Ch-X and I_{PD3} and I_{PD4} from Ch-Y, are obtained, which are sent to a DSP unit, where the four 16-QAM microwave vector signals are separated and recovered, and the phase noise introduced from the transmitter laser source and the LO laser source, and the unstable frequency difference between the transmitter laser source and the LO laser source are cancelled.

At the transmitter, a phase modulator (PM) and a Mach-Zehnder modulator (MZM) in each of the two channels are used for phase and intensity modulation. The MZMs are both biased at the quadrature point. Mathematically, the optical fields of the two orthogonally polarized optical signals at the output of PBS1 can be expressed as

$$E_1(t) = \sqrt{P_s L_1} \cos\left(\frac{\pi S_{RF2}(t)}{2V_{\pi IM1}} + \frac{\pi}{4}\right) e^{j\left[\omega_c t + \varphi_{c1}(t) + \frac{\pi S_{RF1}(t)}{V_{\pi PM1}}\right]} \tag{1.1}$$

$$E_2(t) = \sqrt{P_s L_2} \cos\left(\frac{\pi S_{RF4}(t)}{2V_{\pi IM2}} + \frac{\pi}{4}\right) e^{j\left[\omega_c t + \varphi_{c2}(t) + \frac{\pi S_{RF3}(t)}{V_{\pi PM2}}\right]} \tag{1.2}$$

where P_s is the optical power of the light wave at the output of the transmitter laser source, ω_c is the angular frequency of the light wave, $S_{RF1}(t)$ and $S_{RF3}(t)$ are the two 16-QAM microwave signals applied to the two PMs (PM1 and PM2), $S_{RF2}(t)$ and $S_{RF4}(t)$ are the two 16-QAM microwave signals applied to the two MZMs (MZM1 and MZM2), $\varphi_{c1}(t)$ and $\varphi_{c2}(t)$ are the phase terms of the light waves from the transmitter laser source for Ch-1 and Ch-2, $V_{\pi IM1}$ and $V_{\pi IM2}$ are the half-wave voltages of MZM1 and MZM2, $V_{\pi PM1}$ and $V_{\pi PM2}$ are the half-wave voltages of PM1 and PM2, and L_1 and L_2 are the link losses between the OC and PBS1 for Ch-1 and Ch-2, respectively. Then, the optical signal at the output of PBS1 is transmitted over an SMF and detected at a coherent receiver. To perform coherent detection, an LO laser source is needed. In the proposed MPL, a free-running laser source is used. The optical field at the output of the LO laser source is given by

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

where P_{LO} is the optical power, ω_{LO} is the angular frequency, and $\varphi_{LO}(t)$ is the phase term. The two orthogonally polarized optical signals are demultiplexed by PBS2 into Ch-X and Ch-Y. After coherent detection, four electrical signals at the outputs of the coherent receiver are obtained, which are given by

$$I_{PD1}(t) = A(t)\cos(\Delta\omega t + \varphi_1(t) - \varphi_x + \pi S_{RF1}(t)/V_{\pi PM1}) \tag{3}$$

$$I_{PD2}(t) = A(t)\sin(\Delta\omega t + \varphi_1(t) - \varphi_x + \pi S_{RF1}(t)/V_{\pi PM1}) \tag{4}$$

$$I_{PD3}(t) = B(t)\cos\left(\Delta\omega t + \varphi_2(t) - \varphi_y + \pi S_{RF3}(t)/V_{\pi PM2}\right) \tag{5}$$

$$I_{PD4}(t) = B(t)\sin\left(\Delta\omega t + \varphi_2(t) - \varphi_y + \pi S_{RF3}(t)/V_{\pi PM2}\right) \tag{6}$$

with

$$\Delta\omega = \omega_c - \omega_{LO}, \qquad \varphi_1(t) = \varphi_{c1}(t) - \varphi_{LO}(t),$$
$$\varphi_2(t) = \varphi_{c2}(t) - \varphi_{LO}(t)$$
$$A(t) = 2RL_h\sqrt{P_s P_{LO} L_f L_1}\cos(\pi S_{RF2}(t)/2V_{\pi IM1} + \pi/4)$$
$$B(t) = 2RL_h\sqrt{P_s P_{LO} L_f L_2}\cos(\pi S_{RF4}(t)/2V_{\pi IM2} + \pi/4)$$

where $\Delta\omega$ is the frequency difference between the transmitter laser source and the LO laser source, R is the responsivity of the PD, L_f is the link loss caused by the SMF, φ_1(t), and φ_2(t) are the phase noise terms introduced by the transmitter laser source and the LO laser source, and φ_x and φ_y are the phase terms arising from the polarization mismatch between the received optical signals and the light wave from the LO laser source. To recover RF signal 2 while cancelling the phase noise and the unstable frequency difference, we sum the square of the two currents (I_{PD1} and I_{PD2}) through DSP [7],

$$I_1(t) = I^2_{PD1}(t) + I^2_{PD2}(t) \propto P_s P_{LO}\left[1 - \pi S_{RF2}(t) / V_{\pi IM1}\right] \tag{7}$$

Also, by summing the squared of the other two signals (I_{PD3} and I_{PD4}), RF signal 4, as shown in Fig. 1, can be recovered. As can be seen the two recovered signals are both free from the phase noise and the unstable frequency difference.

To recover RF signal 1, zero padding is applied to RF signal 1 at the transmitter. At the coherent receiver, the detected zero padding signal, $I'_{PD1}(t)$ and $I'_{PD2}(t)$can be rewritten as

$$I'_{PD1}(t) = A(t)\cos\left(\Delta\omega t + \varphi'_1(t) - \varphi_x\right) \tag{8}$$

$$I'_{PD2}(t) = A(t)\sin\left(\Delta\omega t + \varphi'_1(t) - \varphi_x\right) \tag{9}$$

where $\varphi'_1(t)$ is the phase noise in the detected signal when the phase-modulated signal is zero padded.

Through DSP, we obtain,

$$\begin{aligned} I_2(t) &= \operatorname{atan}\left[\left(I_{PD2} \times I'_{PD1} - I_{PD1} \times I'_{PD2}\right) / \right. \\ &\qquad \left. \left(I_{PD1} \times I'_{PD1} + I_{PD2} \times I'_{PD2}\right)\right] \\ &= \operatorname{atan}\left\{\tan\left[\pi S_{RF1-16QAM}(t) / V_{\pi PM1} \right.\right. \\ &\qquad \left.\left. + \varphi_1(t) - \varphi'_1(t)\right]\right\} \end{aligned} \tag{10}$$

Apparently, if the spectrum of the noise $\varphi_1(t) - \varphi'_1(t)$ does not overlap with that of the transmitted RF signal 1, RF signal 1 can be selected by a bandpass filter which is free from the phase noise and unstable frequency difference. Also, RF signal 3 can be recovered by the same method. Note, due to instability of the frequency difference ($\Delta\omega$ in (8) and (9) may not be equal to $\Delta\omega$ in (3), (4), (5), (6)), the frequency difference may not be cancelled completely through (10). Then, a residual frequency difference will be preserved. If we consider the residual frequency difference is much smaller than the symbol rate of RF signal 1, (10) can be rewritten as

$$I'_2(t) = \operatorname{atan}\left\{\tan\left[\pi S_{RF1}(t) / V_{\pi PM1} + \varphi(t) + \sum_{i=1}^{\infty} \omega_i t\right]\right\} \tag{11}$$

where $\sum_{i=1}^{\infty} \omega_i$ is the residual frequency difference. Apparently the third term in the tangent function will accumulate over time and phase jumps will occur. To eliminate the phase jumps, phase unwrapping should be employed [8].

III. EXPERIMENT

An experiment is performed based on the setup shown in Fig. 1. At the transmitter, an optical wave at 1550.0 nm from a tunable laser source (TLS, Agilent N7714A) with a power of 14 dBm and a linewidth of 100 kHz is divided into two channels (Ch-1 and Ch-2) by a 3-dB OC, with the optical wave in each channel being first phase modulated by a 16-QAM microwave signal and then intensity modulated by a second 16-QAM microwave signal. The MZM has a single electrode and is chirp free which is biased at the quadrature point. The half-wave voltages of the four modulators are all around 5V. The four 16-QAM microwave signals are generated by an arbitrary waveform generator (Tektronix AWG7102). The electrical power for each 16-QAM signal is around 7 dBm and the electrical power for each 100-kHz bandwidth of the signal is around -30 dBm. Then, the two optical signals from the two channels are polarization multiplexed at PBS1 and sent to the receiver over a 10-km SMF. At the receiver, optical coherent detection is performed using a coherent receiver (Discovery Semiconductors DP-QPSK 40/100 Gbps Coherent Receiver), with a free running LO laser source (Agilent N7714A) as an LO laser source to detect the two orthogonally polarized optical signals. The optical power and the wavelength of the light wave from the LO laser source are 9.5 dBm and 1550.051 nm. Through tuning PC7, the two polarization multiplexed light waves can be demultiplexed into two channels (Ch-X and Ch-Y) by PBS2. Note that PC7 can be replaced by a dynamic polarization controller [9] in a practical system to avoid manual tuning. In the coherent receiver, Ch-X is used to detect the optical signal from Ch-1, and Ch-Y is used to detect the signal from Ch-2. A digital storage oscilloscope (Keysight DSO-Z 504A) with a sampling rate of 80 GSa/s is employed to perform analog-to-digital conversion. The four sampled signals are processed offline in a computer.

As discussed in Section II, to recover RF signal 1 and RF signal 3, zero padding is needed. In the experiment, the length ratio between the zero padding portion and the signal portion is 1:3. In a practical system, the ratio can be as small as 1:20. The center frequencies of the four 16-QAM microwave signals are 2.5 GHz, and the symbol rate is 625 MSymbol/s, with a total date rate of 10 Gbps. Since the four microwave signals have an identical center frequency, FDM in the microwave domain can be employed to incorporate more microwave channels to further increase the capacity of the MPL.

Fig. 2(a) shows the spectrum of the signal (I_{PD1}) which contains RF signal 1 and RF signal 2 at the output of the coherent receiver. The received optical power for each channel is -10 dBm. As can be seen, the spectra of the two microwave signals are completely overlapped and are up converted to 3.875 GHz and 8.875 GHz because of the wavelength difference between the transmitter laser source and LO laser source. Since the two laser sources are not frequency or phase locked, the frequency difference is not stable. The two 16-QAM microwave signals are separated by DSP. In addition, the phase noise and the unstable frequency difference are also eliminated by DSP. Fig. 2(b) shows the measured EVMs of the recovered microwave signals versus the received optical power. As can be seen, when the optical received optical power is -18 dBm, the EVMs are still less than 14% (the corresponding estimated BERs are less than 10^{-3}. [10]). If state-of-art FEC is employed, error-free transmission can be achieved [11]. The constellations for the four recovered 16-QAM microwave signals when the received optical power for each channel

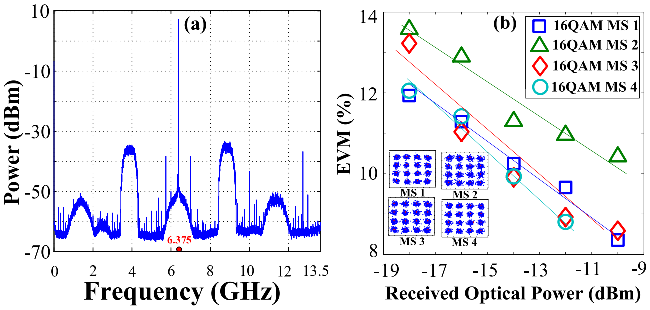

Fig. 2. (a) Spectrum of the signal at the output of the coherent receiver (I_{PD1}), RBW: 76 kHz. (b) EVMs at different received optical power levels of each channel for the four 16-QAM microwave signals transmitted over a 10-km SMF. MS: microwave signal.

is -18 dBm are also shown in Fig. 2(b). They are very clear which proves the effectiveness of the proposed technique to cancel the unstable frequency difference and phase noise introduced from the two laser sources. When the received optical power for each channel is -10 dBm, the measured error vector magnitudes (EVMs) are around 9.5% and the corresponding signal-to-noise ratios (SNRs) are estimated to be 20 dB [10]. If we take the zero padding and the FEC overhead (6.7%) into account, the total net data rate is 9.225 Gbps.

Furthermore, for a vector signal with an SNR of 20 dB, error-free detection of a 64-QAM vector signal can be achieved by using an FEC algorithm (overhead 15%) [10]–[13]. Thus, the total net data rate can reach 12.6 Gbps if the zero padding and the FEC overhead are taken into account.

Since four microwave signals are transmitted over a single fiber link over a single optical carrier, the proposed MPL is suitable for the implementation of 4 × 4 MIMO. In our experimental demonstration, since the AWG can only generate two different microwave signals at the same time, the performance of the proposed MPL with 2 × 2 MIMO is evaluated. In the experiment, two MIMO-OFDM microwave signals are generated by the AWG and are applied to PM2 and MZM2. The center frequency of the two MIMO-OFDM signals is 2.5 GHz and the total data rate is 0.9 Gbps. Each of the two OFDM signals contains 64 subcarriers of which 44 subcarriers are used to carry data. The modulation format for each subcarrier is QPSK. The two MIMO-OFDM signals are received and recovered after offline DSP. In the demonstration, the AWG is also used to perform digital-to-analog conversion (DAC) to generate the two recovered MIMO-OFDM microwave signals after DSP, which are amplified by two electrical amplifiers and sent to two antennas. The electrical amplifier and the antenna in each channel have a gain of 10 dB and 16 dBi, respectively. After 1-m wireless transmission, the two MIMO-OFDM signals are received by another two antennas, and the received signals are demodulated by a software (Keysight VSA). The measured EVMs for the two OFDM signals are 8.8% and 8.4%.

IV. CONCLUSION

A data rate quadrupled MPL based on coherent detection and DSP was proposed and experimentally demonstrated. Four microwave signals were carried by a single optical carrier based on phase modulation and intensity modulation with polarization multiplexing. The four microwave signals were coherently detected at a coherent receiver and recovered by DSP. The phase noise and the unstable frequency difference introduced from the transmitter and LO laser sources were cancelled. An experiment was performed. Error-free transmission of four 2.5-Gbps16-QAM microwave signals with an identical center frequency of 2.5 GHz over a 10-km SMF with a total data rate of 10 Gbps was achieved if FEC was employed. The net data rate of the proposed MPL was 9.225 Gbps if the zero padding and the FEC overhead (6.7%) were taken into account. The number of the transmitted wireless signals was four times that of a regular intensity-modulation and coherent-detection MPL [7]. Since four wireless signals are simultaneously transmitted, the proposed MPL could be used to implement 4 × 4 MIMO. In the experiment, the number of channels that the AWG can generate was two, for MIMO demonstration, only two OFDM signals were generated and transmitted, and a 2 × 2 MIMO MPL was implemented. The measured EVMs of the MIMO-OFDM signals at the wireless terminal were 8.6%. If FEC is employed, error-free transmission can also be achieved

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