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Simple polarization-insensitive coherent RoF link with increased capacity

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A simple polarization-insensitive coherent radio-over-fiber (RoF) link with increased spectrum efficiency and transmission capacity is proposed and demonstrated. Instead of using two polarization splitters (PBSs), two 90° hybrids, and four pairs of balanced photodetectors (PDs) in a conventional polarization-diversity coherent receiver (PDCR), a simplified PDCR with only one PBS, one optical coupler (OC), and two PDs is employed in the coherent RoF link. At the simplified receiver, a novel, to the best of our knowledge, digital signal processing (DSP) algorithm is proposed to achieve polarization-insensitive detection and demultiplexing of two spectrally overlapping microwave vector signals as well as the elimination of the joint phase noise originating from the transmitter and the local oscillator (LO) laser sources. An experiment is performed. The transmission and detection of two independent 16QAM microwave vector signals at identical microwave carrier frequencies of 3 GHz with a symbol rate of 0.5 GSym/s over a 25-km single-mode fiber (SMF) is demonstrated. Thanks to the spectrum superposition of the two microwave vector signals, the spectral efficiency as well as the data transmission capacity is increased.

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Thanks to its low loss, large bandwidth, and immunity to electromagnetic interference (EMI), radio over fiber (RoF), a technique to transmit microwave signals over an optical fiber link, has been considered an effective solution for broadband wireless access networks [1]. To meet the requirement for higher-data-rate transmission, a RoF link with increased transmission capacity is expected. Wavelength division multiplexing (WDM) has been used to transmit multiple microwave signals over a RoF link to increase the transmission capacity [2], but multiple wavelengths are used, making the spectral efficiency low. Space division multiplexing (SDM) can be employed to transmit multiple microwave signals using a single wavelength [3], but special fibers such as multi-core fibers are needed, making its practical applications limited. Polarization division multiplexing (PDM) has also been used in a RoF link to multiplex two microwave signals over a single wavelength [4], with orthogonal-polarization single-sideband (SSB) modulation employed to generate two sidebands with two orthogonal polarizations and carry independent microwave vector signals. In Ref. [5], a RoF link to multiplex two microwave vector signals on a single wavelength was proposed. It was based on intensity modulation and phase modulation in which the intensity-modulated signal is detected directly at a photodetector (PD), but the phase-modulated signal is detected using an on-chip optical Hilbert transformer. Multiplexing two microwave vector signals can also be achieved based on coherent detection [6–8] using a conventional single polarization coherent receiver that consists of a 90° hybrid coupler and two pairs of balanced photodetectors. In Refs. [9,10], two microwave vector signals were polarization multiplexed and transmitted, and a conventional polarization-diversity coherent receiver (PDCR) which consisted of two polarization splitters (PBSs), two 90° hybrids, and four pairs of balanced PDs were used. In Refs. [6–10], the state of polarization (SOP) of the received optical signals was dynamically adjusted by a polarization controller, which increased the receiver complexity.

In this Letter, we propose a simplified PDCR for a coherent RoF link supporting polarization-insensitive receiving with increased spectrum efficiency and transmission capacity. Instead of using two PBSs, two 90° hybrids, and four pairs of balanced PDs, a simplified PDCR with only one PBS, one optical coupler (OC), and two PDs is employed. At the transmitter, two independent microwave vector signals with identical carrier frequencies are intensity modulated on an optical carrier at a dual-drive Mach–Zehnder modulator (DD-MZM) biased at the quadrature transmission point. An optical signal is generated at the output of the DD-MZM, transmitted to the receiver over a single-mode fiber (SMF), and detected at a simplified PDCR to which local oscillator (LO) light is applied [11,12]. The key advantage of using the simplified PDCR is that dynamical polarization control is not needed [6–10], greatly simplifying the implementation of the RoF link. To achieve polarization-insensitive demultiplexing of the two microwave vector signals with identical microwave carrier frequencies, a novel digital signal processing (DSP) algorithm is developed which also eliminates the joint phase noise introduced by the transmitter laser source and the LO laser source. The proposed scheme is evaluated experimentally. In the experiment, two independent 16 quadrature amplitude modulation (16QAM) microwave vector signals at 3 GHz with a symbol rate of 0.5 GSym/s

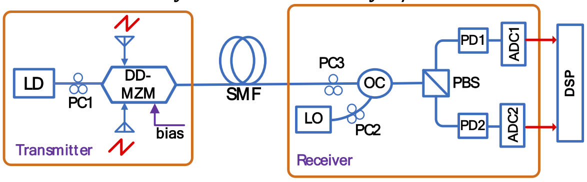

Fig. 1. Schematic of the proposed RoF link.

symbol rate of 0.5 GSym/s are modulated on an optical carrier and transmitted over a 25-km SMF. At the simplified PDCR, the two 16QAM microwave vector signals are received and demultiplexed by a DSP unit. The transmission performance of the RoF link is evaluated by measuring the error vector magnitudes (EVMs) and bit error rates (BERs).

Figure 1 shows the schematic diagram of the proposed RoF link in which a simplified PDCR is employed. At the transmitter, an optical carrier generated by a laser diode (LD) is sent to a DD-MZM via a polarization controller (PC1). The DD-MZM has a Mach–Zehnder interferometer (MZI) structure with a phase modulator in each of the two arms. Two independent microwave vector signals with an identical carrier frequency are applied to the DD-MZM via the two radio-frequency (RF) ports, and a modulated optical signal is generated at the output of the DD-MZM. The modulated signal is transmitted over a SMF to a simplified PDCR to which an LO light is applied. At the receiver, the received optical signal is combined with the LO light at an OC, sent to a PBS, and detected at two PDs. The electrical signals generated at the outputs of the PDs are sampled and processed to demultiplex the two signals and to eliminate the phase noise from the transmitter LD and the LO LD. Assume that the two microwave vector signals are given by $s_{1,2} = m_{1,2}\cos[\omega_m t + \theta_{1,2}(t)]$, where $m_1(t)$ and $m_2(t)$ are the amplitudes, $\theta_1(t)$ and $\theta_2(t)$ are the phases, and ω_m is the carrier frequency of the two microwave vector signals. The microwave vector signals are applied to the DD-MZM via the two RF ports, and the DD-MZM is biased at the quadrature transmission point. Under the small-signal modulation condition, the optical field at the output of the DD-MZM can be approximated as

$$\begin{aligned} E_S(t) &= \sqrt{P_S}\exp j[\omega_S t + \phi_S(t)] \\ &\quad \left[\exp j\left(\frac{\pi}{V_\pi}s_1(t)\right) + \exp j\left(\frac{\pi}{V_\pi}s_2(t) + \frac{\pi}{2}\right)\right] \\ &\approx \sqrt{P_S}\exp j[\omega_S t + \phi_S(t)][1 + j\gamma s_1(t) + j - \gamma s_2(t)] \end{aligned}, \quad (1)$$

where P_s is the optical power, ω_S is the angular frequency, $\phi_S(t)$ is the phase noise of the optical carrier, V_π is the half-wave voltage of the DD-MZM, and $\gamma = \pi/V_\pi$ is the modulation index. From Eq. (1), it can be seen that the two microwave vector signals are linearly mapped to the optical domain with a phase shift of 90° due to the bias of the DD-MZM at the quadrature transmission point. After transmission over the SMF, the modulated optical signal is combined with the LO light and coherently detected at the receiver. The light generated by the LO LD can be expressed as $E_{LO}(t) = \sqrt{P_{LO}}\exp j[\omega_{LO}t + \phi_{LO}(t)]$, where P_{LO} is the optical power, ω_{LO} is the angular frequency, and $\phi_{LO}(t)$ is the phase noise of the LO light. The received optical signal and the LO signal are combined by a 50:50 OC and sent to a PBS. The state of polarization (SOP) of the LO light is adjusted to split equally after the PBS, while the received optical signal has an arbitrary SOP. The polarization directions of the optical signals at the two outputs of the PBS are denoted by H and V, and are given by

$$E_H(t) = \eta_H e^{j\delta_H} E_S(t) + j\frac{\sqrt{2}}{2}e^{j\alpha_H}E_{LO}(t) \quad \textbf{(2a)}$$

$$E_V(t) = \eta_V e^{j\delta_V} E_S(t) + j\frac{\sqrt{2}}{2}e^{j\alpha_V}E_{LO}(t), \quad \textbf{(2b)}$$

where α_H and α_V are the phases in the H and V directions (which depend on the SOP of the LO signal), δ_H and δ_V are the phases in the H and V directions (which depend on the SOP of the received optical signal), and η_H and η_V are the magnitudes in the H and V directions (which depend on the SOP of the received optical signal), with $\eta_H^2 + \eta_V^2 = 1$. The signals at the two outputs of the PBS are sent to the two PDs for optical-to-electrical conversion. The beat signals between $E_H(t)$ and $E_V(t)$ at the two PDs are given by

$$I_H(t) = \eta_H R\sqrt{P_S P_{LO}}\begin{Bmatrix} \cos[\Delta\omega\cdot t + \phi_p(t) + \delta_H - \alpha_H - \pi/4] \\ +\sqrt{2}\gamma s_1(t)\cos[\Delta\omega\cdot t + \phi_p(t) + \delta_H - \alpha_H] \\ -\sqrt{2}\gamma s_2(t)\sin[\Delta\omega\cdot t + \phi_p(t) + \delta_H - \alpha_H] \end{Bmatrix} \quad \textbf{(3a)}$$

$$I_V(t) = \eta_V R\sqrt{P_S P_{LO}}\begin{Bmatrix} \cos[\Delta\omega\cdot t + \phi_p(t) + \delta_V - \alpha_V - \pi/4] \\ +\sqrt{2}\gamma s_1(t)\cos[\Delta\omega\cdot t + \phi_p(t) + \delta_V - \alpha_V] \\ -\sqrt{2}\gamma s_2(t)\sin[\Delta\omega\cdot t + \phi_p(t) + \delta_V - \alpha_V] \end{Bmatrix}, \quad \textbf{(3b)}$$

where $\Delta\omega = \omega_S - \omega_{LO}$ is the frequency difference between the optical signals from the transmitter LD and the LO LD, R is the responsivity of the PDs, and $\phi_p(t) = \phi_S(t) - \phi_{LO}(t)$ is the joint phase noise introduced by the transmitter and LO LDs. As can be seen from Eq. (3a), there is a carrier centered at $\Delta\omega$ in the generated electrical signal along the H direction, which can be extracted by a narrow bandpass filter (BPF). By introducing a phase shift of +45° or −45° into the carrier in the H direction, we have

$$I_H^{c_1}(t) = \eta_H R\sqrt{P_S P_{LO}}\cos[\Delta\omega\cdot t + \phi_p(t) + \delta_H - \alpha_H] \quad \textbf{(4a)}$$

$$I_H^{c_2}(t) = \eta_H R\sqrt{P_S P_{LO}}\sin[\Delta\omega\cdot t + \phi_p(t) + \delta_H - \alpha_H]. \quad \textbf{(4b)}$$

Then, the extracted carriers are used to downconvert the electrical signal along the H direction, which can be expressed as

$$I_H^{m_1}(t) = I_H(t)I_H^{c_1}(t) \quad \textbf{(5a)}$$

$$I_H^{m_2}(t) = I_H(t)I_H^{c_2}(t). \quad \textbf{(5b)}$$

If a lowpass filter (LPF) is used to extract the signal centered at ω_m, the two demultiplexed signals are given by

$$I_{H1}(t) = \left(\sqrt{2}/2\right)\eta_H^2 R^2 P_S P_{LO}\gamma s_1(t) \quad \textbf{(6a)}$$

$$I_{H2}(t) = -\left(\sqrt{2}/2\right)\eta_H^2 R^2 P_S P_{LO}\gamma s_2(t). \quad \textbf{(6b)}$$

As can be seen from Eq. (6), the two microwave vector signals are demultiplexed but dependent on the SOP of the received optical signal. The same process can be applied to the V direction; the two demultiplexed signals are then given by

$$I_{V1}(t) = \left(\sqrt{2}/2\right)\eta_V^2 R^2 P_S P_{LO}\gamma s_1(t) \quad \textbf{(7a)}$$

$$I_{V2}(t) = -\left(\sqrt{2}/2\right)\eta_V^2 R^2 P_S P_{LO}\gamma s_2(t). \quad \textbf{(7b)}$$

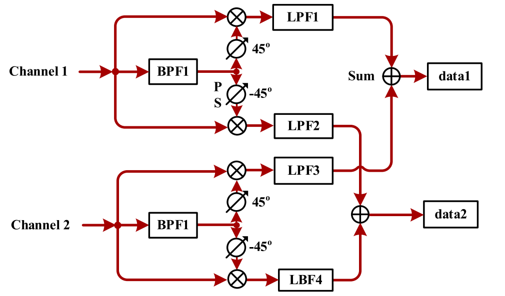

Fig. 2. DSP algorithm used to demultiplex the two microwave vector signals that are SOP independent.

Finally, by adding each of the demultiplexed signals from the two channels, we have

$$I_1(t) = I_{H1}(t) + I_{V1}(t) = \left(\sqrt{2}/2\right) R^2 P_S P_{LO} \gamma s_1(t) \quad \textbf{(8a)}$$

$$I_2(t) = I_{H2}(t) + I_{V2}(t) = -\left(\sqrt{2}/2\right) R^2 P_S P_{LO} \gamma s_2(t). \quad \textbf{(8b)}$$

As can be seen from Eq. (8), the two microwave vector signals are recovered and are independent of the SOP of the received optical signal. The flow chart of the DSP algorithm is shown in Fig. 2. There are two identical channels. Taking channel 1 as an example, a digitized signal is sent a digital BPF (BPF1) to extract the microwave carrier, which is phase shifted by ±45°. The phase-shifted microwave carriers are multiplied by the received signal and then applied to two LPFs (LPF1 and LPF2). The two microwave vector signals, which are polarization independent, are recovered by summing the signals from LPF1 and LPF3 and from LPF2 and LPF4.

An experiment based on the setup shown in Fig. 1 is performed. A continuous-wave (CW) optical signal with a linewidth of 100 kHz is generated and sent to a DD-MZM (Fujitsu, FTM7821ER), which has a half-wave voltage of 4 V and a 3-dB bandwidth of 10 GHz. Two independent 16QAM signals centered at 3 GHz with a symbol rate of 0.5 GSym/s are generated by an arbitrary waveform generator (AWG, Keysight M8195A) and applied to the DD-MZM via the two RF ports. The bias of the DD-MZM is adjusted to allow the DD-MZM to operate at the quadrature transmission point. A modulated optical signal is generated at the output of the DD-MZM and transmitted to the receiver over a 25 km SMF. In the receiver, CW light with a linewidth of 100 kHz is used as the LO light. The power of the LO signal is set to be 9 mW. The received optical signal and the LO light are combined by a 50:50 OC. The optical spectrum of the combined signal is shown in Fig. 3. The power of the LO signal is split equally at the output of the PBS by adjusting PC2. To emulate the rotation of the SOP of the optical signal after transmission, a PC (PC3) is placed before the polarization-diversity receiver to adjust the SOP.

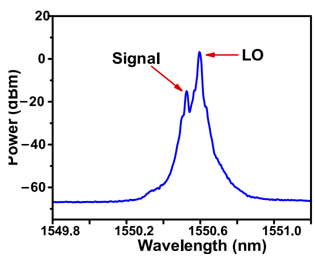

Fig. 3. Measured optical spectrum at the output of the OC.

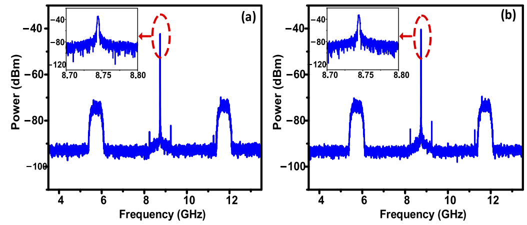

Fig. 4. Optical spectra for the optical signals along the (a) H and (b) V directions. Inset: Enlarged view of the generated microwave carrier.

The signals at the two outputs of the PBS are applied to two PDs (New Focus, 1414) with a bandwidth of 25 GHz and a responsivity of 0.7 A/W. After optical-to-electrical conversion at the PDs, the two detected electrical signals are sampled by a digital storage oscilloscope (Agilent DSO-X 93204A) with a sampling rate of 80 GSa/s. The sampled signals are sent to a DSP unit to demodulate the two microwave vector signals.

Figures 4(a) and 4(b) shows the measured spectra of the generated electrical signals for the H and V directions, respectively. The received optical power is −8 dBm. As can be seen, a microwave carrier at 8.75 GHz, which is the offset frequency between light waves from the transmitter LD and the LO LD, is generated. An enlarged view of the generated microwave carrier is shown in the insets of Fig. 4. The microwave carrier contains the joint phase noise originating from the transmitter and the LO LDs. Figures 5(a) and 5(b) show the spectra of the demultiplexed microwave vector signals for the H direction. The EVMs of the demultiplexed two microwave vector signals are 14.22% and 14.89%, and the constellations of the 16QAM signal are shown in the insets of Figs. 5(a) and 5(b). Figures 5(c) and 5(d) show

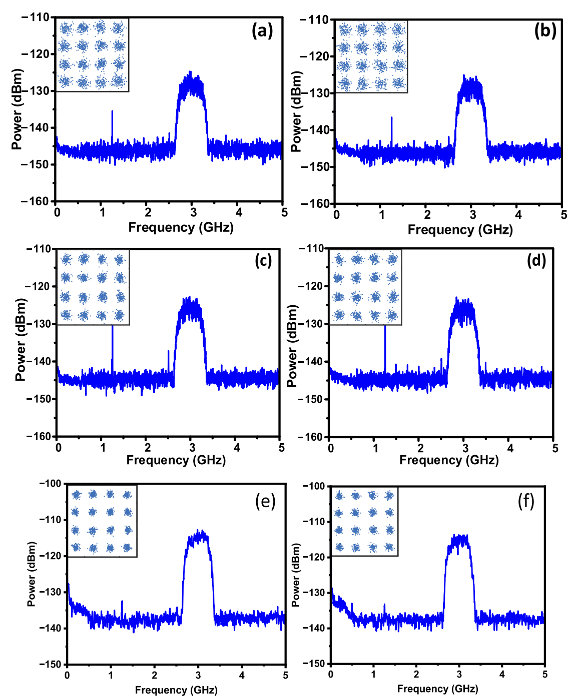

Fig. 5. Two downconverted and demultiplexed microwave signals along (a), (b) the H direction and (c), (d) the V direction. (e), (f) Combined signals. Insets: Constellations of the 16QAM signals.

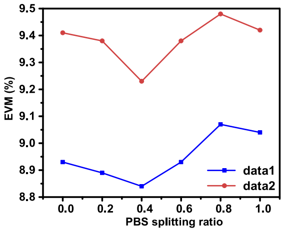

Fig. 6. Measured EVMs for different PBS splitting ratios.

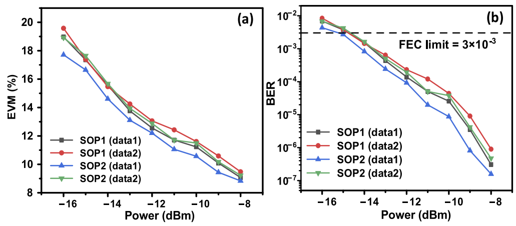

Fig. 7. Measured (a) EVMs and (b) BERs at different received optical power levels.

the spectra of the demultiplexed two microwave signals for the V direction. The EVMs of the two microwave vector signals are 10.91% and 11.37%, and the constellations of the 16QAM signal are shown in the insets of Figs. 5(c) and 5(d). Figures 5(e) and 5(f) show the spectra of the two combined microwave signals. The EVMs of the two demultiplexed microwave vector signals are now 8.88% and 9.21%, which are smaller than the EVMs of a single channel for the H or V direction. The combined signals are polarization insensitive, as shown in Eq. (8). To evaluate the independence of the performance of the RoF link with respect to the SOP, we tune the SOP of the received optical signal by adjusting PC3. When the SOP is adjusted, the splitting ratio of the PBS is changed. Here, the splitting ratio is defined as the power ratio between the H channel and the sum of the powers of the H and V channels. The measured EVMs for splitting ratios of 0, 0.2, 0.4, 0.6, 0.8, and 1 when the received optical power is −8 dBm are shown in Fig. 6. As can be seen, the variation of the EVM for data1 is within 0.23%, while the variation for data2 is 0.25%. The polarization independence is validated. The EVM performance of the two demultiplexed microwave vector signals versus the received optical power for the SOPs with the largest variations is shown in Fig. 7(a). As can be seen, for such a large variation of the SOP, the variations of the EVMs are within 0.25% when the received optical power is −8 dBm. The BERs are also calculated from the EVMs, and are shown in Fig. 7(b). Again, the variations of the BERs are very small. For example, when the received optical power is −14 dBm, the BERs are 1.53×10^{-3} and 1.44×10^{-3} for one SOP and 8.27×10^{-4} and 1.63×10^{-3} for the other. The small variations come from the small discrepancy between the H and V channels and the noise of the receiver. All the BERs are well within the forward error correction (FEC) limit. By employing a state-of-the-art FEC technique, a raw BER of up to 3×10^{-3} can be improved to an effective BER of 1×10^{-15} at the expense of a 6.7% overhead [13], and error-free transmission can be achieved.

In summary, we have proposed and experimentally demonstrated a RoF link incorporating a simplified PDCR supporting polarization-insensitive receiving with increased spectral efficiency and transmission capacity. The key contribution of the work is the development of a new DSP algorithm by which two spectrally overlapping microwave vector signals at identical carrier frequencies over a single optical wavelength can be effectively detected and demultiplexed, and the detection is polarization insensitive. The operation of the proposed RoF link was experimentally evaluated. Error-free transmission of two independent 16-QAM microwave vector signals with identical carrier frequencies of 3 GHz and a symbol rate of 0.5 GSym/s over a 25-km SMF that was polarization insensitive was demonstrated. When the received optical power is larger than about −14 dBm, error-free transmission can be achieved with FEC. Since only one polarization is used in the proposed RoF link, the other polarization can be used to double the link capacity.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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