Microwave vector signal transmission over an optical fiber based on IQ modulation and coherent detection

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A novel approach to transmitting two vector signals using a single optical carrier based on IQ modulation and coherent detection is proposed and demonstrated. In the proposed system, two quadrature phase-shift keying (QPSK) signals are IQ modulated on an optical carrier with one polarization state using a dual-parallel Mach–Zehnder modulator (DP-MZM). The optical carrier with an orthogonal polarization state is not modulated but transmitted with the modulated optical wave. At the receiver, the two orthogonally polarized light waves are separated and sent to a coherent detector, where the two QPSK signals are separated and demodulated. An experiment is performed. The transmission of two QPSK signals at 2 GHz with a data rate of 1 Gbps is implemented over a 25 km single-mode fiber. The performance of the transmission in terms of error vector magnitude is evaluated.

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The transmission of microwave signals over optical fibers has been a topic of research interest and has been extensively studied in the last few years. The transmission of radio signals over fiber, or radio-over-fiber (RoF), can find numerous applications such as antenna remoting, cable TV, and broadband wireless access [1–2]. Due to the limited spectrum resources, modulation formats with high spectral efficiency should be employed, such as phase-shift keying (PSK) and quadrature-amplitude modulation (QAM). These modulated signals are also called vector signals. In the past few years, numerous techniques have been proposed to implement RoF transmission employing vector signal modulation and transmission [3–6]. In a RoF system, it is usually required that multiple wireless signals are transmitted over a single fiber. In a conventional RoF system, however, multiple wireless signals should be modulated on different optical carriers to avoid spectrum aliasing because the wireless signals may have an identical carrier frequency. For example, in a multi-input multi-output system, the wireless signals from different antennas have an identical microwave carrier frequency. Also, in a RoF wavelength-division-multiplexed-passive-optical network (WDM-PON), multiple users may send different signals carried by microwave carriers with an identical frequency. A solution is to use different wavelengths to carry different wireless signals [7,8]; thus the system becomes complicated and costly since multiple optical wavelengths and multiple modulators should be used. On the other hand, coherent detection [9,10] provides great flexibility in modulation formats, as information can be encoded in amplitude and phase, or alternatively in both in-phase (I) and quadrature (Q) components of a carrier, which is the most promising detection technique because of its low noise and high spectral efficiency.

In this Letter, we propose a novel photonic approach to transmitting two microwave vector signals in a single microwave carrier employing IQ modulation and coherent detection. In the proposed system, a linearly polarized light wave is split into two orthogonally polarized light waves, with one being modulated by the two microwave vector signals, and the other without modulation but transmitted with the modulated light wave in the same fiber. At the receiver, the two optical waves with orthogonal polarization states are separated and sent to a coherent detector, where the two microwave vector signals are separated and demodulated. Compared with conventional microwave vector signal transmission in a fiber link, the key contributions and difference of the work here are to transmit two different microwave vector signals with the same microwave carrier frequency using a single optical carrier, which greatly reduces the number of the optical carriers and modulators needed to carry the microwave vector signals. In addition, in the proposed method coherent detection is employed, which reduces the influence of the noise from the photodetector (PD). A proof-of-concept experiment is performed. Two 1 Gbps quadrature phase-shift keying (QPSK) signals at a microwave carrier frequency of 2 GHz modulated on a single optical carrier are transmitted over a 25 km single-mode fiber (SMF). The performance of the transmission in terms of constellation diagrams and error vector magnitude (EVM) measurements is evaluated.

Figure 1 provides a conceptual diagram illustrating the proposed microwave vector signal transmission system based on IQ modulation and coherent detection. Optical multicarriers are generated from a single-wavelength source using a multicarrier generator, which is then de-multiplexed at an optical wavelength demultiplexer (De-MUX). For a given wavelength, it is split into two orthogonally polarized light waves at a polarization beam

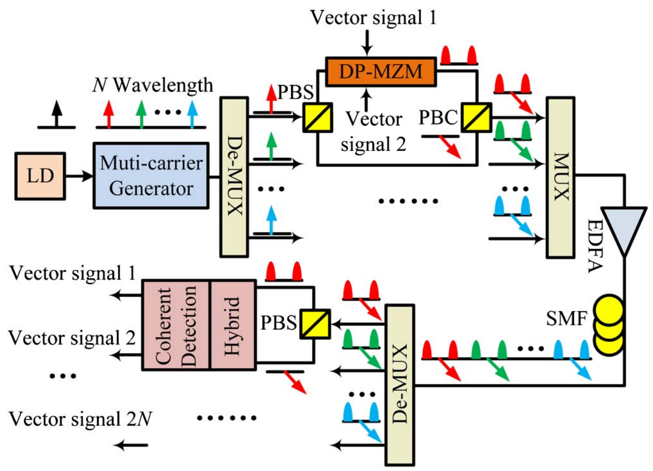

Fig. 1. Conceptual diagram illustrating microwave vector signal transmission based on IQ modulation and coherent detection. LD, laser diode; De-MUX, demultiplexer; PBS, polarization beam splitter; DP-MZM, dual-parallel Mach–Zehnder modulator; PBC, polarization beam combiner; MUX, multiplexer; EDFA, erbium-doped fiber amplifier; SMF, single-mode fiber.

splitter (PBS), with one light wave IQ modulated by two microwave vector signals with an identical microwave carrier frequency at a dual-parallel Mach–Zehnder modulator (DP-MZM), and the other without data modulation. The two light waves are then combined at the polarization beam combiner (PBC). All the wavelengths are then multiplexed using a wavelength multiplexer (MUX) before being amplified by an erbium-doped fiber amplifier (EDFA) and transmitted over a length of SMF. At the receiver, a De-MUX is used to separate the wavelengths. Again, for one wavelength, a PBS is used to separate the two orthogonally polarized light waves, which are then sent to a coherent detector. At the output of the coherent detector, two vector signals are obtained. For a system with N wavelengths, $2N$ vector signals can be transmitted.

For a given optical wavelength, two orthogonally polarized light waves are obtained at the output of the PBS, with one sent to the DP-MZM, and the other sent to the PBC. Assume that the two vector signals applied to the DP-MZM are I(t) and Q(t). The DP-MZM is working at an IQ modulation condition (both sub-MZMs are biased at the minimum transmission points and the main-MZM is biased to introduce a π^2 phase shift), the optical signal at the output of the DP-MZM can be expressed as

$$E_x(t) = \frac{1}{2}E_x\left[\begin{array}{l}\cos\left(\frac{\pi(2I(t)-V_\pi)}{2V_\pi}\right)\exp(j\omega_c t)\\ +\cos\left(\frac{\pi(2Q(t)-V_\pi)}{2V_\pi}\right)\exp\left(j\omega_c t + j\frac{\pi}{2}\right)\end{array}\right]$$
$$\approx \frac{1}{2}E_x\left[\gamma I(t)\exp(j\omega_c t) + \gamma Q(t)\exp\left(j\omega_c t + j\frac{\pi}{2}\right)\right], \quad (1)$$

where E_x and ω_c are the amplitude and angular frequency of the input optical field to the DP-MZM, V_π is half-wave voltage of the DP-MZM, and $\gamma = \pi/V_\pi$. In deriving Eq. (1), the small modulation condition is considered. It is shown in Eq. (1) that the two vector signals are IQ modulated on an optical carrier.

The other light wave from the PBS is not modulated. Mathematically, it is expressed as

$$E_y(t) = E_y \exp(j\omega_c t), \quad (2)$$

where E_y is the amplitude of the optical field of the unmodulated optical carrier.

The two orthogonally polarized light waves are then combined at the PBC and multiplexed with other wavelengths and transmitted over an SMF. At the receiver, the wavelengths are demultiplexed. For one wavelength, the two orthogonally polarized light waves are split by a second PBS and sent to a coherent detector. The coherent detector consists of an optical hybrid and two pairs of PDs [9]. The hybrid functions to generate four outputs from the combination of the two input signals with phase differences of 0°, 180°, 90°, and –90°. Then the four outputs are sent to the two pairs of PDs. The principle of the coherent detector is shown in Fig. 2.

The two light waves shown in Eqs. (1) and (2) are sent to the coherent detector. At the output of the optical hybrid, we have four output signals, which are expressed as

$$E_1(t) = E_x(t) + E_y(t), \quad (3)$$

$$E_2(t) = E_x(t) + E_y(t)\exp(j\pi), \quad (4)$$

$$E_3(t) = E_x(t) + E_y(t)\exp(j\pi/2), \quad (5)$$

$$E_4(t) = E_x(t) + E_y(t)\exp(-j\pi/2). \quad (6)$$

The signal at the outputs of the upper pair of the PDs can be expressed as

$$i_{\mathrm{upper}}(t) = E_1(t)E_1^*(t) - E_2(t)E_2^*(t) = 2E_xE_y\gamma I(t). \quad (7)$$

Similarly, the signal at the outputs of the lower pair of the PDs can be expressed as

$$i_{\mathrm{lower}}(t) = E_3(t)E_3^*(t) - E_4(t)E_4^*(t) = 2E_xE_y\gamma Q(t). \quad (8)$$

As can be seen from Eqs. (7) and (8), the two microwave vector signals are successfully recovered at the outputs of the coherent detector.

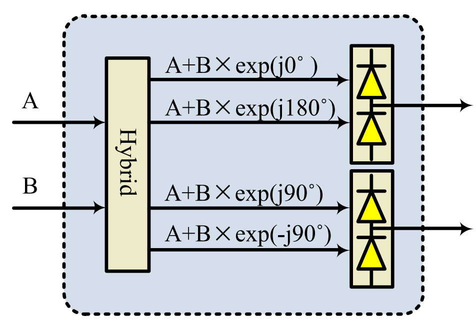

Fig. 2. Principle of the coherent detector. The coherent detector consists of an optical hybrid and two pairs of PDs.

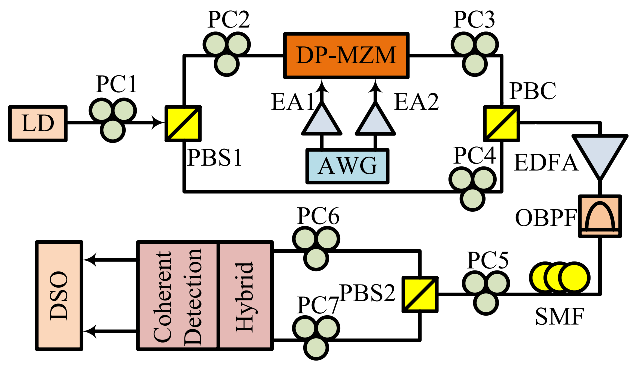

Fig. 3. Experimental setup for vector signal transmission and detection. LD, laser diode; PC, polarization controller; PBS, polarization beam splitter; DP-MZM, dual-parallel Mach–Zehnder modulator; AWG, arbitrary waveform generator; PBC, polarization beam combiner; EDFA, erbium-doped fiber amplifier; OBPF, optical bandpass filter; SMF, single-mode fiber; DSO, digital sampling oscilloscope.

An experiment based on the setup shown in Fig. 3 is performed. A light wave at 1545.45 nm from an LD (Anritsu MG9638A) is sent to PBS1 via PC1. One light wave at one output port of PBS1 is sent to a DP-MZM (JDS-U) via PC2, which is driven by two 1 Gbps QPSK signals centered at a microwave carrier frequency of 2 GHz generated by an arbitrary waveform generator (Tektronix AWG710210) and amplified by two electrical amplifiers, EA1 and EA2, with a 10 dB gain. The other light wave at the other output port of PBS1 is not modulated and is sent to a PBC via PC4. The two sub-MZMs in the DP-MZM are both biased at the minimum transmission points, and the main-MZM in the DP-MZM is biased to introduce a π^2 phase shift. The optical signal at the output of the DP-MZM is then sent to the PBC via PC3. PC3 and PC4 are used to make the polarization states of the two input signals align with the two orthogonal polarization directions of the PBC. Then the optical signal is filtered by an optical bandpass filter (OBPF), after amplification by an EDFA, to filter out the amplified spontaneous-emission noise of the EDFA. Then the optical signal is transmitted over 25 km SMF before being sent to PBS2 via PC5 to separate the two orthogonally polarized light waves. The two physically separated orthogonally polarized light waves are sent to the coherent detector via the two input ports (Discovery Semiconductor Inc.) via PC6 and PC7. The recovered electrical signals are captured by a digital sampling oscilloscope (DSO, Agilent DSO-X 93204A), and then demodulated by postprocessing using a computer.

To verify the transmission performance of the system, we first measure the constellation diagrams of the two QPSK signals with and without fiber transmission. In the experiment, we control PC1 to let the two orthogonally polarized light waves at the outputs of PBS2 to have an identical optical power. The two QPSK signals I(t) and Q(t) are recovered by the coherent detector, obtained at its two outputs. The constellation diagrams of I(t) and Q (t) at three specific received optical power levels for back-to-back and 25 km SMF transmission are shown in Fig. 4. As can be seen, the constellations of the two QPSK signals do not significantly degrade after 25 km SMF transmission, which indicates that fiber transmission has little influence on the transmission performance. It is also noticed that the two QPSK signals have a small difference in constellation diagrams with a given received optical power. The small difference may be caused by the bias drift of the DP-MZM in the measurement, and the unequal amplitudes of the electrical signals applied to the DP-MZM.

We then evaluate the performance of the system in terms of EVM for the recovered two QPSK signals. The EVMs of the two QPSK signals are measured for back-to-back and 25 km SMF transmission for a received optical power from −3 to −17 dBm. The results are shown in Fig. 5. As can be seen, the EVM performance for the transmission of the I(t) and Q(t) signals after 25 km SMF transmission are slightly degraded.

Note that the EVM measurements for the two microwave vector signals for both the back-to-back and 25 km SMF transmission are not exactly identical. The reasons for the nonidentical measurements for the two signals include: (1) the bias voltages applied to the DP-MZM may deviate from the set values in the experiment, which leads to unstable transmission characteristics of the two QPSK signals; (2) the two orthogonally polarized light waves may not exactly orthogonal, which may lead to some cross talk during the fiber transmission; (3) the two orthogonally polarized light waves are split and recombined by two PBSs, which may make the phase difference between the two light waves change slowly due to environmental changes, such as the temperature

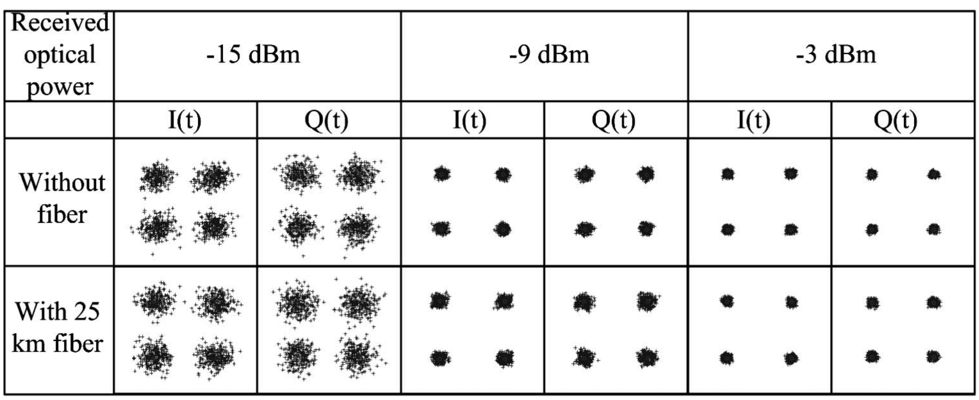

Fig. 4. Constellation diagrams of the two QPSK signals at different received optical power.

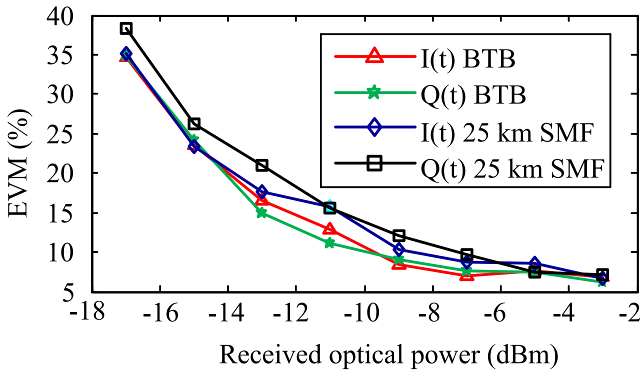

Fig. 5. EVM curve versus received optical power. BTB, back-to-back; SMF, single-mode fiber.

change. However, these problems can be solved if a bias control circuit is employed. In addition, if the discrete devices are replaced by a photonic integrated circuit, the performance in terms of stability will also be improved.

In conclusion, a photonic approach to transmitting two microwave vector signals using a single optical carrier based on IQ modulation and coherent detection was proposed and experimentally demonstrated. The key contribution of the work was the use of a DP-MZM to modulate two vector signals with an identical microwave carrier frequency on one light wave and transmit an orthogonally polarized light wave without modulation over the same fiber for coherent detection. Thus the number of optical carriers and modulators needed to carry the vector signals were reduced by half. Since balanced detections were employed, the noise due to the PDs was also reduced. The proposed technique was investigated experimentally. Error-free transmission of two 1 Gbps QPSK signals at a microwave carrier frequency of 2 GHz over a 25 km SMF was realized. The constellation and the EVM performance of the two QPSK signals with or without SMF transmission were also measured and compared. The results show that the performance was not significantly degraded after 25 km SMF transmission.

The system stability was also studied. For the short term, the system was operating in a room environment without seeing significant degradation in the transmission performance. Since, the system was implemented based on discrete components, the long-term stability is still an issue. A solution is to integrate the system using a photonic integrated circuit.

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