A Novel Direct Detection Microwave Photonic Vector Modulation Scheme for Radio-Over-Fiber System

Chun-Ting Lin, Sheng-Peng Dai, Jason (Jyehong) Chen, Po Tsung Shih, Peng-Chun Peng, and Sien Chi

***Abstract*—This letter demonstrates the feasibility of a novel direct detection microwave photonic vector modulation scheme for the radio-over-fiber (RoF) system. Unlike the traditional double-sideband with optical carrier suppression modulation scheme, which can carry only the on–off keying data format, the proposed scheme encodes the electrical vector signal on either the upper sideband (USB) or the lower sideband (LSB) only and a pure optical subcarrier on the other sideband. Therefore, phase and amplitude information will be preserved after direct detection. A frequency doubling scheme is employed to reduce the cost of RoF systems. Additionally, the relative intensity between USB and LSB can be easily tuned by adjusting the individual power of electrical driving signals to optimize the performance of the optical radio-frequency signals. A proof-of-concept experiment is conducted by using a 1.25 Gb/s BPSK signal at a carrier frequency of 20 GHz. After transmission over 50-km single-mode fiber, the receiver sensitivity penalty is less than 0.5 dB.**

***Index Terms*—Mach–Zehnder modulator (MZM), photonic vector signal, radio-over-fiber (RoF).**

I. Introduction

RADIO-OVER-FIBER (RoF) systems have attracted considerable attention for their potential use in future broadband wireless access networks. Since the available bandwidth is limited, high spectral efficiency vector modulation formats, such as M-ary phase shift keying (PSK) and quadrature amplitude modulation (QAM) are the preferred modulation schemes. Recently, optical radio-frequency (RF) signal generations using an external Mach–Zehnder modulator (MZM), electro absorption modulator (EAM), or phase modulator (PM) together with a fiber grating, which are based on double-sideband (DSB), single-sideband (SSB), and double-sideband with optical carrier suppression (DSBCS) modulation schemes, have been demonstrated [1]–[7]. Since the optical RF signals are weakly modulated due to the narrowness of the linear modulation region, those that have undergone DSB and SSB modulation suffer from inferior sensitivities associated with the limited optical modulation index (OMI). Furthermore, the DSB signal experiences the problem of performance fading because of fiber dispersion. Among these modulation schemes, the DSBCS modulation scheme has been demonstrated in the millimeter-wave range to offer better spectral efficiency, a lower bandwidth requirement for electrical components, and superior receiver sensitivity following transmission over a long distance [2].

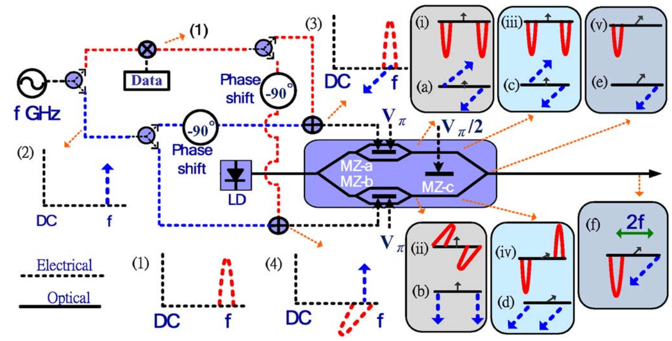

Fig. 1. Conceptual diagram of generating direct detection optical RF signals. (1)–(4): Electrical input signal. (i)–(v): Optical spectrum of data signal. (a)–(e): Optical spectrum of sinusoidal signal. (f): Optical spectrum of RF signal.

However, all of the proposed DSBCS schemes can support only an ON–OFF keying (OOK) format [2]–[4], and none can transmit vector modulation formats, such as M-ary PSK and QAM signals, which are of the utmost importance for wireless applications. This letter proposes a novel method for generating optical direct-detection RF signals using a new DSBCS modulation scheme that can carry vector signals. In addition, a frequency doubling scheme is employed to reduce the bandwidth requirement of electronic components, which is an important issue for RoF systems in the millimeter-wave band.

II. Concept of Proposed System

Fig. 1 schematically depicts the principle of the proposed optical direct-detection RF signal generation. A commercially available integrated x-cut $LiNbO_3$ MZM [8], comprising three single-electrode MZMs, is key to generating optical RF signals. Two sub-MZMs (MZ-a and MZ-b) are embedded in each arm of the main modulator (MZ-c). When both MZ-a and MZ-b are biased at the null point, the generated optical spectrum consists of an upper sideband (USB) and a lower sideband (LSB) with optical carrier suppression. Except when the phase difference between the two paths is -90°, the RF signals sent into the MZ-a and MZ-b are exactly the same. When MZ-c is biased at the quadrature point, either USB or LSB will be eliminated at the output of the integrated MZM. For the sinusoidal signal, when the phase difference is -90° at the path to MZ-a, the polarity

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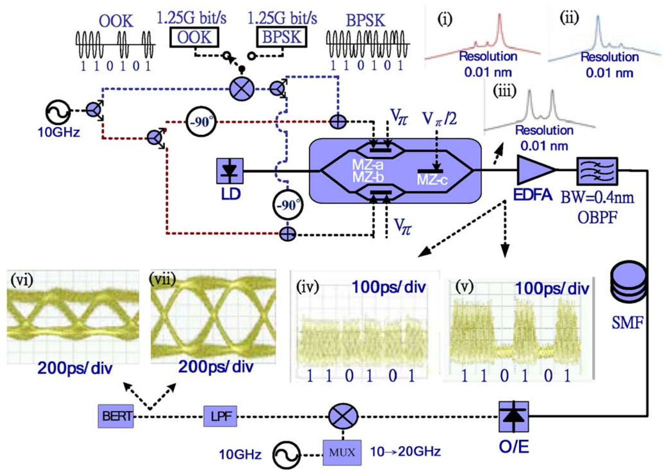

Fig. 2. Experimental setup for vector signal generation and transmission using one external modulator. (i) New optical subcarrier. (ii) Data-encoded signal. (iii) Optical RF signal. (iv) Waveform of optical BPSK signal. (v) Waveform of optical OOK signal. (vi) Eye diagram of OOK signal. (vii) Eye diagram of BPSK signal.

of LSB in inset (c) opposes that in inset (d). The LSB will be eliminated whereas the USB is obtained. For a data-modulated signal with a phase difference of -90° at the path to MZ-b, only the LSB will be obtained. Therefore, the optical RF signal, consisting of the two-tone lightwave, which can be converted into an electrical RF signal by square-law photodiode (PD) detection, can be produced at the output of the transmitter. Since the RF signal is modulated only on either the USB or the LSB, the amplitude and phase of the vector signal will be preserved after direct detection. Therefore, the proposed system can generate not only OOK signals but also PSK and QAM signals. Additionally, the relative intensity between USB and LSB can be easily tuned by adjusting the individual power of the electrical sinusoid and data signals to optimize the performance of the optical RF signals [7].

III. Experimental Setup and Results

Fig. 2 depicts the experimental setup. The RF signals can be any vector signals, including M-ary PSK and QAM signals. Here, only detailed experimental results of BPSK signal are presented. The OOK signal is also demonstrated to provide baseline system information. A 1.25-Gb/s BPSK or OOK pseudorandom binary sequence (PRBS) signal with word length of $2^{31}-1$ is up-converted to the center frequency of 10 GHz. The RF signal is then split using a 90° hybrid coupler to drive MZ-a and MZ-b. The RF signal is modulated on the optical LSB, as shown in inset (ii) of Fig. 2. The same mechanism is used to split the 10-GHz sinusoidal signal to drive MZ-a and MZ-b. A new optical carrier can be generated on the USB of the original carrier by 10 GHz, as shown in inset (i) of Fig. 2. Inset (iii) of Fig. 2 presents the optical spectrum when both signals are turned on. Notably, the distance between the RF signal and the new optical carrier is 20 GHz. The generated RF signal is then amplified using an EDFA and filtered through a 0.4-nm optical filter to suppress the ASE noise. Then, an optical attenuator is used to set the optical launched power to 0 dBm before transmission to prevent fiber nonlinearity. The 25- or 50-km single mode fiber (SMF) is used to evaluate the transmission penalty of the system. After square-law PD direct detection, the electrical RF signal is

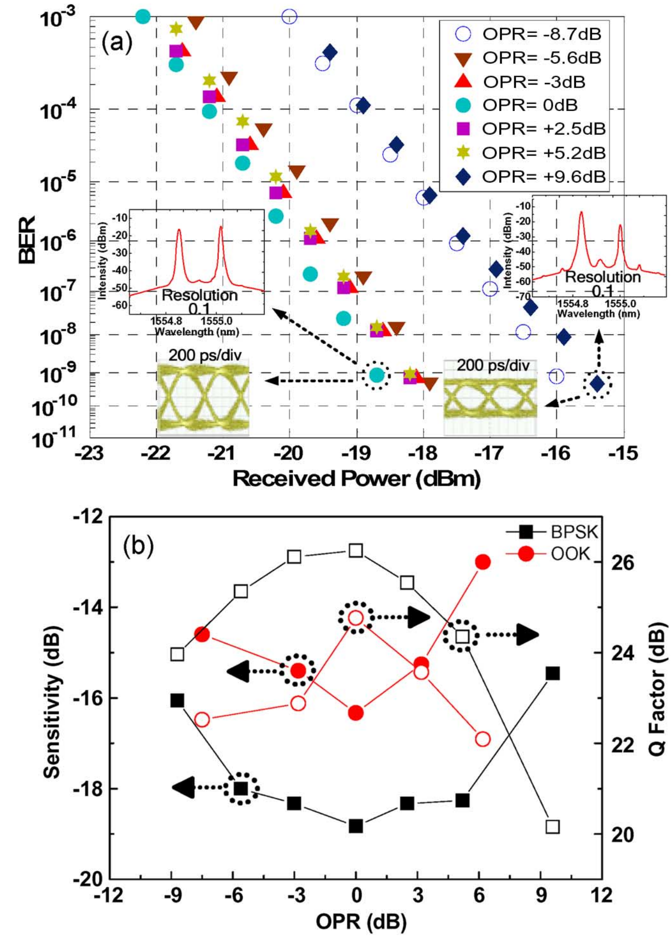

Fig. 3. (a) BER curves of BPSK RF signals versus OPR. (b) Receiver sensitivity of OOK and BPSK RF signals at BER of 10^{-9} and simulation Q factor versus OPR.

down-converted to the baseband signal by a 20-GHz oscillator and a mixer. Then, both BPSK and OOK baseband signals are tested by a bit-error-rate (BER) tester.

The relative intensity between the optical carrier and the optical data-modulated subcarrier strongly influences the performance of the optical RF signals [7]. Fig. 3 illustrates the receiver sensitivity of the BPSK and OOK RF signals with different optical power ratios (OPR) between the 10-GHz subcarrier and the data-encoded subcarrier (OPR $= Pd/Ps$, Ps and Pd are the optical powers of the 10-GHz subcarrier and the data-encoded subcarrier, respectively.). The 10-GHz sinusoidal modulation index $(\mathrm{MI} = \frac{\mathrm{V_{P-P}}}{2\mathrm{V_{\Pi}}})$ for driving MZ-a and MZ-b is set to 0.1, and the data modulation index is tuned to achieve different OPRs. The optimal OPR of both BPSK and OOK RF signals is 0 dB. Therefore, the optical power of the 10-GHz subcarrier is identical to that of the data-modulated subcarrier for RF signal generation using optimal OPR, and the result is consistent with previous work [7]. Fig. 3 also presents the Q factor, which is evaluated using commercial simulation software (VPI WDM-Transmission Maker 7.1). The optimal experiment OPR is in agreement with the simulation result.

Notably, the receiver sensitivity of the BPSK signal is better than that of the OOK signal. The reason is that as the bit of the OOK signal is "0", the data-encoded subcarrier is off but the 10–Hz subcarrier is on. Hence, the power of the 10-GHz

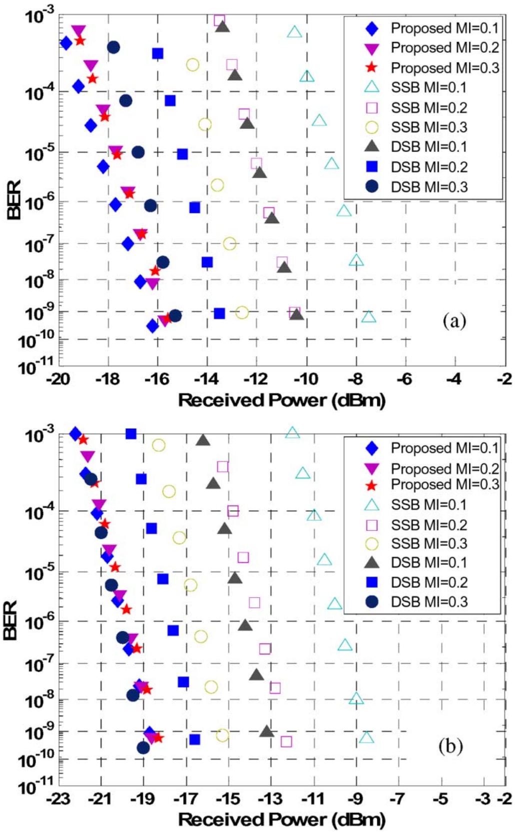

Fig. 4. BER curves of the (a) OOK and (b) BPSK (b) RF signals versus data MI.

subcarrier at the bit "0" is wasted and the receiver sensitivity of the OOK signal is degraded. Therefore, the eye opening of the BPSK down-converted signal is larger than that of the OOK down-converted signal at the same optical power as shown in insets (iv) and (v) of Fig. 2.

Since the MZM has a nonlinear E/O conversion response, the nonlinear distortions including harmonic distortion and intermodulation distortion of the generated RF signal cannot be avoided. To reduce the nonlinear distortion, the MI for driving MZM needs to be kept relatively small. However, RoF signals using DSB and SSB modulation with small MI suffer from inferior sensitivities due to limited OMI, as shown in Fig. 4. As the data MI decreases from 0.3 to 0.1, the performance of the RF signals using DSB and SSB modulation will severely degrade (about 5 dB for both DSB and SSB). For the proposed system using optimal OPR, the receiver sensitivity penalties of both OOK and BPSK RF signals are negligible as $0.1 < \mathrm{MI} < 0.3$, which as a factor is very important for multicarrier or OFDM RoF systems where nonlinear distortion is the primary factor that determines system performance.

Since the proposed scheme can generate a high-purity two-tone lightwave, the generated RF signals do not suffer periodic fading issues due to fiber dispersion. Only in-band distortion of the data-encoded subcarrier induced by fiber dispersion is considered. Since the date rate of the RF signals is only 1.25 Gb/s, the fiber chromatic penalty can be ignored as transmission length is less than 50 km. Fig. 5 shows the BER curves

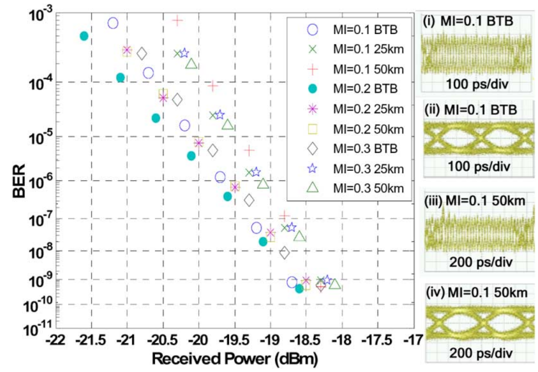

Fig. 5. BER curves of BPSK RF signals following 50-km SMF transmission.

of the BPSK RF signals using optimal OPRs after transmission over 50 km SMF. The receiver sensitivity penalty is less than 0.5 dB.

IV. Conclusion

This letter demonstrates a new DSBCS modulation scheme that can carry vector signals. The electrical vector signal is encoded on either USB or LSB, and a new subcarrier is generated on the other. The proposed architecture utilizes the carrier suppression technique to achieve frequency doubling, and the optimal OPR is investigated by adjusting the individual power of electrical driving signals. To reduce the MZM nonlinear response, the MI is kept small with negligible sensitivity penalty. We successfully transmit a 1.25-Gb/s BPSK signal over 50-km SMF with a sensitivity penalty of less than 0.5 dB.

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