Photonic vector signal generation employing a novel optical direct-detection in-phase/quadrature-phase upconversion

Wen-Jr Jiang,[2] Chun-Ting Lin,[1,*] Chung-hung Ho,[1] Chia-Chien Wei,[3] Po-Tsung Shih,[2]
Jason (Jyehong) Chen,[2] and Sien Chi[4]

[1] *Institute of Photonic Systems, National Chiao Tung University, Tainan 711, Taiwan*
[2] *Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan*
[3] *Department of Applied Materials and Optoelectronic Engineering, National Chi Nan University, Nautou 545, Taiwan*
[4] *Department of Photonics Engineering, Yuan Ze University, Chung Li 320, Taiwan*
**Corresponding author: jinting@mail.nctu.edu.tw*

Received July 21, 2010; revised October 15, 2010; accepted October 16, 2010;
posted October 19, 2010 (Doc. ID 132090); published November 30, 2010

This work demonstrates the feasibility of the generation of an RF direct-detection vector signal using optical in-phase/quadrature-phase (I/Q) upconversion. The advantage of the proposed transmitter is that no electrical mixer is needed to generate the RF signal. Therefore, I/Q data of RF signals are processed at baseband at the transmitter, which is independent of the carrier frequency of the generated RF signal. A 10 Gb/s 16 quadrature amplitude modulation signal is experimentally demonstrated. Following transmission over a 50 km single-mode fiber, the power penalty is negligible. Moreover, I/Q imbalance of the proposed transmitter is studied and compensated by digital signal processing, which is both numerically and experimentally verified.

OCIS codes: 060.5625, 060.4510.

Radio-over-fiber (RoF) systems have attracted considerable interest because of their potential use in future broadband wireless communications. The RoF system that distributes RF signals over an optical fiber is a promising approach because of its high bandwidth and low propagation loss. To provide a higher-data-rate transmission, high spectral efficiency modulation formats are required, because the bandwidth of a wireless channel is limited. Therefore, high-order quadrature amplitude modulation (QAM) is a good candidate. The generation of optical RF vector signals using an external Mach–Zehnder modulator (MZM) based on double-sideband (DSB) and single-sideband (SSB) modulation schemes have been recently demonstrated [1]. However, both modulation schemes suffer from sensitivity degradation because of the limited optical modulation index. Additionally, the DSB signal undergoes performance fading owing to fiber dispersion. Furthermore, to generate an RF vector signal in a high-frequency band, an electrical mixer with a typical conversion loss of more than 8 dB is required to upconvert vector signals to an intermedium or RF, which degrades the performance of the upconverted RF vector signals, especially at the higher frequency. Recently, the generation of optical RF signals by all-optical upconversion has been extensively investigated [2–9]. However, the corresponding system requires at least two modulators to upconvert the in-phase (I) and quadrature-phase (Q) signals and occupies much more optical bandwidth than traditional DSB and SSB modulation schemes [4–8]. Moreover, [9] needs a local oscillator for homodyne or heterodyne detection, which is not practical for access applications.

This investigation proposes an optical RF vector signal generation approach using optical upconversion and studies its performance both numerically and experimentally. The advantage of this architecture is that it requires no electrical mixer. Furthermore, since the proposed system generates only one unmodulated optical subcarrier and one modulated optical subcarrier, i.e., the SSB format, the system does not suffer from RF fading. Moreover, the optimization of their power ratio can be simply realized, because the power of two optical subcarriers can be adjusted independently. Without an electrical mixer to upconvert the RF vector signal, the proposed system can support a high-data-rate signal with excellent performance. However, an important factor that significantly affects system performance is the precision of controlling the amplitude and phase of the input I/Q signals. Therefore, the Gram–Schmidt orthogonalization procedure (GSOP) that compensates for the I/Q imbalance is proposed and demonstrated. With I/Q imbalance compensation, both simulation and experimental results verify a significant increase in the tolerance of both amplitude mismatching and conjugate misalignment.

Figure 1 presents the proposed optical transmitter to generate a direct-detection wideband optical vector signal. The optical field is modulated by an integrated modulator, which consists of three submodulators: two submodulators for in-phase modulation (MZ-a) and quadrature-phase modulation (MZ-b), and another submodulator (MZ-c) for controlling the phase difference between MZ-a and MZ-b. The optical field at the input of the integrated modulator is given by $E_{\text{in}}(t) = E_o \cos(\omega_c t)$, where E_o and ω_c are the amplitude and angular frequency of the optical field, respectively. MZ-a and MZ-b are both biased at the minimum transmission point, and MZ-c maintains a 90° phase shift between the output signals of MZ-a and MZ-b. The optical field at the output of the transmitter is given by

$$E_{\text{out}}(t) = -E_o \sin(\pi I(t)/2V_\pi)\cos(\omega_c t) + E_o \sin(\pi Q(t)/2V_\pi)\sin(\omega_c t), \qquad (1)$$

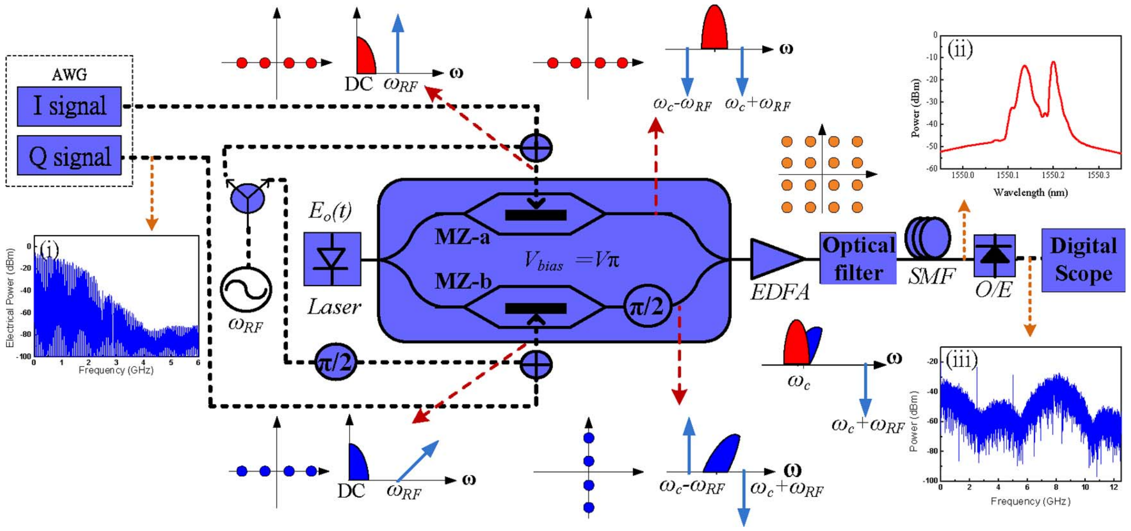

Fig. 1. (Color online) Experimental setup of proposed optical I/Q upconversion system.

where $I(t)$ and $Q(t)$ are the in-phase and quadrature-phase data of the vector signal, respectively.

To realize the direct-detection optical vector signals, an unmodulated optical subcarrier is generated at $\omega_c + \omega_{\mathrm{RF}}$, as shown in Fig. 1. Two sinusoidal waves with the same RF frequency but a 90° phase difference are sent to MZ-a and MZ-b after being combined with the electrical I/Q signals. The unmodulated optical subcarrier with carrier suppression is generated at an angular frequency of $\omega_c + \omega_{\mathrm{RF}}$. The high-order terms and the interference between the unmodulated and modulated subcarriers caused by the nonlinear transfer function of an MZM can be neglected when the modulation depth is small. Accordingly, the optical field at the output of the transmitter can be approximated as

$$\begin{aligned} E_{\mathrm{out}}(t) \cong E_o\{&-J_0(m)\sin(\pi I(t)/2V_\pi)\cos(\omega_c t) \\ &+ J_0(m)\sin(\pi Q(t)/2V_\pi)\sin(\omega_c t) \\ &- 2J_1(m)\cos((\omega_c + \omega_{\mathrm{RF}})t)\}, \end{aligned} \tag{2}$$

where m is $(V/2V_\pi)\pi$ and V is the amplitude of the electrical sinusoidal driving signal. As determined by square-law photodetection, the beating terms of the modulated and unmodulated signals generate the desired RF vector electrical signal at the frequency of ω_{RF}, and can be expressed as

$$\begin{aligned} I_{\mathrm{photo}} = RJ_0(m)J_1(m)E_0^2[&\sin(\pi I(t)/2V_\pi)\cos(\omega_{\mathrm{RF}}t) \\ &- \sin(\pi Q(t)/2V_\pi)\sin(\omega_{\mathrm{RF}}t)], \end{aligned} \tag{3}$$

where R is the responsivity of the photodiode. Since the modulation depth is small, the equation can be further simplified as

$$\begin{aligned} I_{\mathrm{photo}} = {}& (\pi/2V_\pi) \\ &\times RJ_0(m)J_1(m)E_0^2[I(t)\cos(\omega_{\mathrm{RF}}t) \\ &- Q(t)\sin(\omega_{\mathrm{RF}}t)]. \end{aligned} \tag{4}$$

Because the generated optical signal has one modulated subcarrier and one unmodulated subcarrier, the proposed system can generate not only on–off-keying signals but also phase-shift keying, QAM, and orthogonal frequency-division multiplexing signals. However, the I/Q data transmit over different paths to the modulator, resulting in amplitude mismatch and conjugate misalignment. The possible origins of the amplitude mismatch can be the difference between the powers of the I/Q signals, the different V_π of MZ-a and MZ-b, and the imperfect splitting ratio between MZ-a and MZ-b. Furthermore, conjugate misalignment arises because MZ-c does not provide an exact 90° phase shift between the output signals of MZ-a and MZ-b. The amplitude mismatch can cause signal distortion, and the conjugate misalignment causes interference between the I/Q signals. These effects can be expressed analytically:

$$\begin{aligned} I_{\mathrm{photo}} = {}& (\pi/2V_\pi) \\ &\times RJ_0(m)J_1(m)E_0^2[aI(t)\cos(\omega_{\mathrm{RF}}t) \\ &- Q(t)\sin(\omega_{\mathrm{RF}}t + \theta)], \end{aligned} \tag{5}$$

where a and θ are the amplitude mismatch and the conjugate misalignment parameter, respectively. Figure 2

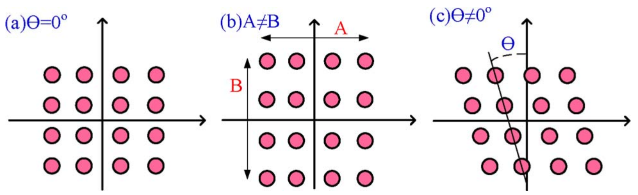

Fig. 2. (Color online) Concept of imbalance effect.

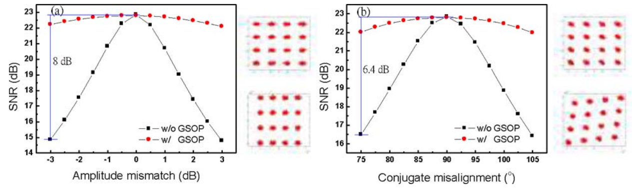

Fig. 3. (Color online) Simulation results of amplitude mismatch and conjugate misalignment.

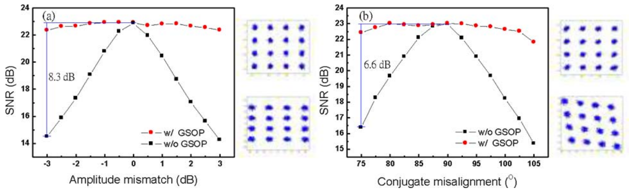

Fig. 4. (Color online) Experimental imbalance results.

presents the concept of amplitude mismatch and conjugate misalignment. While Fig. 2(a) exhibits the ideal constellation of a square 16-QAM signal, the amplitude mismatch results in unequal powers of the I/Q signals shown in Fig. 2(b). Moreover, the conjugate misalignment leads an oblique constellation depicted in Fig. 2(c), and the I/Q signals interfere with each other. To solve the issue of I/Q imbalance, the GSOP is proposed [9] to reduce the imbalance effect.

The VPI WDM-TransmissionMaker is used to simulate the effects of I/Q imbalance and the correction using the GSOP. Figures 3(a) and 3(b) present the simulation results concerning a 16-QAM signal. A 3 dB amplitude mismatch and a 15° conjugate misalignment result in 8 and 6.4 dB signal-to-noise ration (SNR) degradation, respectively. The SNR degradations of ~0.6 and ~0.9 dB corresponding to a 3 dB amplitude mismatch and a 15° conjugate misalignment, respectively, are compensated by the GSOP. The results clearly reveal the criticality of the I/Q imbalance for the 16-QAM format and the great performance improvement by the GSOP. The simulation results reveal that the GSOP can remove most penalties caused by the I/Q imbalance for different modulation formats.

Figure 1 presents the experimental setup of the proposed system. Since the baseband 16-QAM signal is complex, the real and imaginary parts are sent from channel one and channel two of a Tektronix AWG7102 arbitrary waveform generator (AWG). The 16-QAM signal data rate is 10 Gb/s, as shown in inset (i) of Fig. 1. To realize optical direct detection, a new optical subcarrier is generated in one sideband at a frequency that is 8 GHz higher than the original optical carrier, as shown in inset (ii) of Fig. 1. Following square-law detection, an electrical 2.5 GSymbol/s signal at 8 GHz is generated and captured by a Tektronix DPO 71254 with a 50 Gb/s sampling rate, as shown in inset (iii) in Fig. 1. The off-line DSP program is used to demodulate the vector signal. The bit error rate (BER) performance is calculated from the measured SNR [2]. Figure 4 presents the experimental results obtained using GSOP compensation. Since the frequency response of the AWG, amplifier, and modulators is uneven, the feed-forward equalizer is used to reduce the intersymbol interference effect. Figures 4(a) and 4(b) present experimental results concerning the 16-QAM signal, and the GSOP compensation can decrease the SNR degradation from 8.3 to 0.6 dB (from 6.6 to 0.6 dB) due to a 3 dB amplitude mismatch (15° conjugate misalignment). The results also verify the criticality of the I/Q imbalance for the 16-QAM format. Furthermore, the experimental results agree well with the simulation results. Figure 5 plots the transmission BER curves of the 16-QAM signal with the GSOP compensation. A receiver sensitivity of −11.7 dBm is achieved at a BER of 10^{-9} in the back-to-back case. The penalty at the BER of 10^{-9} is negligible following 50 km single-mode fiber (SMF) transmission. The inserts in Fig. 5 present the constellation diagrams, and no obvious distortion is observed after fiber transmission.

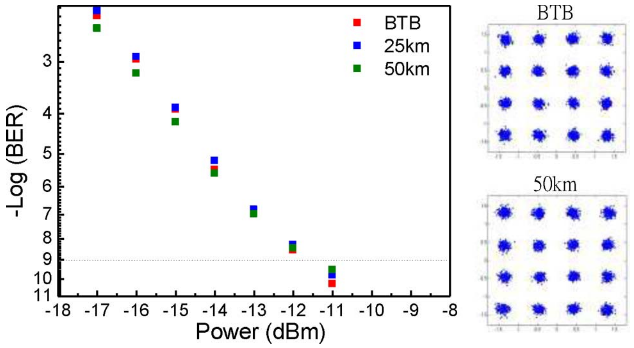

Fig. 5. (Color online) BER curves of a 10 Gb/s 16-QAM signal.

This study proposes the generation of an RF vector signal using all-optical I/Q upconversion for direct detection. 10 Gb/s 16-QAM signals at 8 GHz are demonstrated in both the numerical simulation and the experiment. By applying the GSOP, an SNR degradation of less than 1 dB is achieved for the 16-QAM signals, as a 3 dB amplitude mismatch or 15° conjugate misalignment is applied. Moreover, after transmission over a 50 km SMF, a negligible power penalty is observed.

The authors thank the National Science Council of Taiwan (NSCT) for financially supporting this research under contracts NSC99-2221-E-009-047-MY3 and NSC 99-2221-E-009 -046 -MY3.

References

1. J. Yu, Z. Jia, L. Yi, G. K. Chang, and T. Wang, IEEE Photonics Technol. Lett. **18**, 265 (2006).
2. C. K. Weng, Y. M. Lin, and W. I. Way, J. Lightwave Technol. **26**, 643 (2008).
3. J. L. Corral, R. Sambaraju, M. A. Piqueras, and V. Polo, Opt. Lett. **33**, 1294 (2008).
4. P. Candelas, J. Lightwave Technol. **21**, 496 (2003).
5. T. Ye, C. Yan, Q. Chang, and Y. Su, Opt. Commun. **281**, 4648 (2008).
6. Y. Zhang, K. Xu, J. Li, J. Wu, X. Hong, and J. Lin, Opt. Lett. **33**, 2332 (2008).
7. R. Sambaraju, V. Polo, J. L. Corral, and J. Marti, Opt. Lett. **33**, 1833 (2008).
8. Y. Zhang, K. Xu, R. Zhu, J. Q. Li, J. Wu, X. B. Hong, and J. T. Lin, J. Lightwave Technol. **26**, 2604 (2008).
9. I. Fatadin, S. J. Savory, and D. Ives, IEEE Photonics Technol. Lett. **20**, 1733 (2008).