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Optics Letters

Optical I/Q modulation utilizing dual-drive MZM for fiber-wireless integration system at K_a -band

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In this Letter, a fiber-wireless integration system at K_a -band adopting heterodyne coherent detection is proposed and experimentally demonstrated. Optical I/Q up-conversion is realized with a low-cost dual-drive Mach-Zehnder modulator (DD-MZM) instead of the traditional I/Q nested MZM. To avoid non-convergence during constant-modulus-algorithm-based equalization, DC elimination is applied to suppress the ultra-high peak in the frequency domain after frequency down-conversion and symbol-phase-average-processing-based coarse phase noise estimation. Using DD-MZM for optical I/Q modulation, transmission, and reception of single polarization, 20-Gbit/s quadrature phase shift keying (QPSK) over 40-km single-mode fiber (SMF) and 5-m free space at K_a -band is demonstrated. © 2019 Optical Society of America

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Enhanced mobile broadband (eMBB) communication is one of three typical application scenarios defined for 5G. To meet the bandwidth requirement of eMBB communication services, such as ubiquitous 4 k/8 k high-definition television (HDTV), cloud service, and virtual reality/augmented reality (VR/AR), new radio (NR) is proposed to implement in the 5G [1,2]. K_a -band (26.5–40 GHz) with large available bandwidth has been appointed as the higher frequency band in the 5G NR. Photonics-aided millimeter-wave (mm-wave) signal transmission technology is more practical than the bandwidth-limiting all-electric technology to realize the generation, modulation, and detection of the broadband mm-wave signal [3–14]. K_a -band is at a lower frequency boundary of mm-wave; photonics-aided fiber-wireless integration is an effective solution to achieve low-cost and high-capacity K_a -band signal transmission. In recent proposed fiber-wireless integration schemes, quadrature-amplitude modulation (QAM) at the transmitter side and coherent detection at the receiver are realized to enable high-spectral efficiency (SE) and long-distance signal transmission. Advanced digital signal processing (DSP) algorithms are also employed to solve the problems of fiber chromatic

dispersion (CD), frequency offset, and phase noise compensation [15]. Heterodyne detection instead of homodyne detection is used for optical-to-electrical (O/E) conversion to avoid broadband electrical I/Q up-conversion in the base station (BS) [4–14,16–18]. While optical I/Q up-conversion is necessary to simultaneously transmit intensity and phase of the vector signal, in the above-mentioned fiber-wireless integration systems, optical I/Q conversions are all implemented with an I/Q nested Mach-Zehnder modulator (MZM) [3–14,17,18]. Three child MZMs are contained within the I/Q nested MZM; thus, the cost is relatively high, and it is not conducive to photonics integration.

In this Letter, we propose to use a dual-drive MZM (DD-MZM) instead of I/Q MZM to achieve optical I/Q up-version. Compared to an I/Q modulator, the cost of a DD-MZM is approximately reduced to 1/3. In Ref. [19], dual-single-sideband (SSB) modulation is realized with a DD-MZM for photonic vector mm-wave signal in fiber-wireless integration systems. Receiver sensitivity is very low, since the mm-wave signal is generated by two modulated sideband beats. In addition, the frequency range and quality of the generated mm-wave signal are limited by the bandwidth of the modulator and photodiode (PD). To deal with these two problems, a new fiber-wireless integration system utilizing DD-MZM for optical I/Q modulation is proposed in this Letter. DD-MZM is applied for baseband 10 Gbaud vector quadrature phase shift keying (QPSK) signal modulation, and optical heterodyne detection is adopted with better performance at the expense of an additional optical local oscillator (LO). To transmit high-level QAM in the fiber-wireless integration system, the I/Q nested MZM scheme with lower modulation nonlinearity is more suitable than the proposed DD-MZM scheme, while high-level QAM signal can be transmitted in the proposed DD-MZM scheme with nonlinear compensation algorithms. In this Letter, a seamlessly integrated fiber-wireless system that delivers a 20 Gbit/s QPSK signal at K_a -band adopting heterodyne coherent detection is demonstrated. After 40-km single-mode fiber (SMF) and 5-m free-space wireless transmission, the bit error ratio (BER) of 20 Gbit/s QPSK signal is still below the hard decision forward error correction (HD-FEC) threshold (3.8×10^{-3}).

During optical I/Q up-conversion with DD-MZM, the baseband signal in-phase and quadrature components are expressed with $I(t)$ and $Q(t)$, respectively. In the DD-MZM, two parallel phase modulators (PMs) are composed when the bias voltage difference of two PMs is set to $V_\pi/2$, and the output of DD-MZM can be expressed as [20]

$$\begin{aligned} E_o(t) &= E_i(t) \left\{ e^{j\left[\frac{\pi}{V_\pi}I(t) - \frac{\pi}{2}\right]} + e^{j\left[\frac{\pi}{V_\pi}Q(t)\right]} \right\} \\ &= E_i(t) \left\{ -j * e^{j\left[\frac{\pi}{V_\pi}I(t)\right]} + e^{j\left[\frac{\pi}{V_\pi}Q(t)\right]} \right\}. \end{aligned} \quad (1)$$

When the $I(t)$ and $Q(t)$ are small signals, e^{j*x} parts in Eq. (1) can be approximated with Taylor expansion as

$$e^{j*x} = 1 + j*x + \frac{(j*x)^2}{2!} + \frac{(j*x)^3}{3!} + \frac{(j*x)^4}{4!} + \dots, \quad (2)$$

while in the optical I/Q up-conversion with I/Q nested MZM, the approximation is from $\sin(x)$ parts, and it can be divided into

$$\sin(x) = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \frac{x^7}{7!} \dots \quad (3)$$

Comparing Eq. (2) with Eq. (3), we find that additional even-power series exist during the approximation of e^{j*x} parts. To avoid serious nonlinearity in modulation, the amplitude of modulated signal should be limited to a very small range. Then the output signal can be further expressed as

$$\begin{aligned} E_o(t) &\approx E_i(t) \left\{ -j \left[1 + j * \frac{\pi}{V_\pi} I(t) \right] + \left[1 + j * \frac{\pi}{V_\pi} Q(t) \right] \right\} \\ &= E_i(t) \left\{ \frac{\pi}{V_\pi} * [I(t) + j * Q(t)] + 1 - j \right\}. \end{aligned} \quad (4)$$

From Eq. (4), optical I/Q up-conversion is achieved with DD-MZM, but the DC component $1-j$ also appears during modulation. Due to the heterodyne detection scheme used in a fiber-wireless integration system, the interferences originate from the beating between signals, and the DC component is out-of-band when the frequency difference between signals and LO laser carriers is large enough in heterodyne detection.

To verify the effectiveness of optical I/Q up-conversion with DD-MZM in a fiber-wireless integration system, the proof-of-concept seamlessly integrated fiber-wireless experimental setup is shown in Fig. 1. At the optical baseband transmitter, there is an external cavity laser (ECL) at 1549.425 nm with less than 100-kHz linewidth and output power of 14.5 dBm. The continuous-wavelength (CW) lightwave from ECL is modulated by a Fujitsu FTM-7937 DD-MZM with 4 V half-wave voltage,

and the DD-MZM is driven by a 10 Gbaud Nyquist pulse-shaped electrical baseband QPSK signal with 0.1 roll-off factor. The QPSK signal is generated by a Fujitsu 80 GSa/s sampling rate digital-to-analog converter (DAC). The I/Q components from DAC are amplified by two linear electrical amplifiers (EAs) with 20 dB gain. The V_{p-p} of the signal after EAs is approximately 2.5 V. For optical up-conversion, the difference of phase between two parallel PM arms is controlled at $\pi/2$, which is the quadrature point of DD-MZM. The generated signal is launched into 40-km SMF with 4.5-dBm input power, which has 9-dB loss and 17-ps/km/nm CD at 1550 nm without optical dispersion compensation.

After 40-km SMF transmission, an optical LO at 1549.65 nm with less than 100-kHz linewidth has 28.8-GHz frequency offset ($\Delta f = 22.8$ GHz) relative to the modulated optical carrier. Since only single polarization signal transmission is demonstrated, a polarization controller (PC) is used to track the polarization of received signal. Figure 2 shows the optical spectra of signal and LO optical carrier with 0.01-nm resolution; the LO to signal carrier power ratio is fixed at 8 dB during the following test.

The signal and LO are combined with a polarization-maintaining optical coupler (PMOC) and then injected into a variable optical attenuator (VOA) to adjust the power of input signal into a 40-GHz Finisar PD. After O/E conversion, the electrical intermediate frequency (IF) signal at K_a -band is boosted by a 40-GHz EA before it is launched into the horn antenna (HA) to radiate the signal out into free space. After 1–5-m wireless free-space transmission, the signal is received by another K_a -band HA and then connected to an 80-GSa/s sampling rate Lecory oscilloscope (OSC). The gain of 40-GHz EA after PD is 19 dB from 26–40 GHz, and the saturated output power is 20 dBm. No amplified saturation will be observed when the PD input optical power is lower than 0 dBm. The transmitter and receiver HA are both 25 dBi. The atmospheric loss can be ignored with only 5-m wireless transmission. The antenna feedline loss is 3 dB, and the path loss is 75.36 dB at a 28-GHz central frequency after 5-m wireless delivery according to the Friis equation [17]. The total aforementioned link power loss is -9.36 dB. Figure 3 shows the photos of the K_a -band wireless subsystem. Figures 3(a) and 3(b) show the wireless transmitter and receiver, respectively. In this Letter, only single polarization signal transmission is realized due to the lack of a 40-GHz PD and HAs in the experimental setup.

The captured symbols are processed with offline DSP algorithms shown in Fig. 4(a). Frequency offset is first obtained with FFT-based rough frequency offset estimation (FOE).

Fig. 1. Experimental setup of seamlessly integrated fiber-wireless system with DD-MZM for optical I/Q up-conversion.

Fig. 2. Optical spectra of signal and LO optical carrier.

Fig. 3. Photos of (a) wireless TX and (b) wireless RX.

The length of symbols in FOE is set to only 8192 for low implementation complexity, and the corresponding frequency resolution is about 10 MHz. We have to point out here that the DC component in Eq. (4) leads to an ultra-high power peak within the signal band during O/E conversion, the electrical spectrum of the received signal is shown in Fig. 4(b); an obvious peak frequency can be observed around 28.8 GHz. The peak is actually a narrow-band interference due to the phase noise, and this narrow-band peak after frequency down-conversion will cause wrong convergence during equalization. The narrow-band interference needs to be eliminated before equalization. Thus, after digital frequency down-conversion, first-stage carrier phase estimation (CPE) with symbol phase average (SPA) processing is done to compensate the residual frequency offset and phase noise to make the interference as narrow as possible, and the optimization of length of symbols during SPA will be discussed later in this Letter. The ultra-high peak in the frequency domain is suppressed with DC elimination. As the phase information can be well preserved after an optical coherent heterodyne, receiver electronic dispersion compensation (EDC) can be implemented for fiber transmission after re-sampling according to Ref. [21]; re-timing and 13-taps constant modulus algorithm (CMA)-based equalization are applied to recover QPSK symbols. The second-stage Viterbi-Viterbi phase estimation [8] with 200 adjacent symbols is done before BER calculation. Constellations of the received sample after the aforementioned offline DSP without

Fig. 4. (a) Offline RX DSP and (b) electrical spectrum of signal.

Fig. 5. Constellations of received sample after different offline DSP stages.

and with SPA-based first CPE are shown in Fig. 5. As the resolution during FOE is only about 10 MHz, it is impossible to totally suppress the peak in the frequency domain after DC elimination without SPA-based first CPE. The residual peak wrongly converges after CMA and second CPE; thus, the constellations of the received sample are converged to one point after offline DSP without SPA-based first CPE.

To optimize the length of average symbols of SPA in first-stage CPE, measured BER of the received signal after 40-km SMF and 2-m wireless transmission with -7 dBm received optical power (ROP) versus length of average symbols is shown in Fig. 6. The optimized average length is chosen as 501, taking both performance and latency into consideration. In the following test, the length of average symbols is fixed at 501.

The transmission curve between bias voltage and output optical power of DD-MZM in the experimental setup is measured and shown in Fig. 7(a). The quadrature point of the DD-MZM is 0.6 V; the bias voltage needs to be set at 0.6 V to realize optical I/Q up-conversion. To verify this, we measure the BER of the received signal in optical back-to-back (OBTB) with -11 dBm ROP by adjusting the bias voltage of the DD-MZM, and the results are given in Fig. 7(b). Apparently, the optimized bias voltage is exactly 0.6 V, which is just the quadrature point. I/Q imbalance will arise during optical I/Q up-conversion when the bias point is not optimized at quadrature point, and BER performance becomes worse.

For 20-Gbit/s QPSK signal delivery, the measured BERs of signal versus ROP of the signal injected into PD both in OBTB and after 40-km SMF with/without 2-m wireless link are shown in Fig. 8. Between OBTB only and OBTB with 2-m wireless transmission, 0.5-dB penalty appears at the BER of 3.8×10^{-3} after 2-m wireless transmission; this penalty is introduced by link loss in a wireless link. No penalty is seen

Fig. 6. BER versus length of average symbols.

Fig. 7. (a) Transmission curve of DD-MZM and (b) BER of received signal versus different bias voltage of DD-MZM.

Fig. 8. Measured BER versus ROP.

after 40-km SMF transmission, since the 40-km fiber CD can be completely compensated in the offline DSP. The required ROP is -11 dBm for 20 Gbit/s QPSK after 40-km SMF and 2-m wireless transmission at BER of 3.8×10^{-3} .

Figure 9 gives BER versus different wireless distances from 1 m to 5 m with 40-km fiber transmission when the ROP of the received signal is -6 dBm. The BER performance degrades with the increase in wireless delivery distance, while it is still less than 1×10^{-4} after 40-km fiber and 5-m wireless delivery. The constellations of received signal after 0-m and 5-m wireless delivery are both inserted in Fig. 9 as insets. Obvious distortions can be seen in the constellations even without

Fig. 9. Measured BER versus different wireless distances.

wireless link, this is induced mainly by the second-order term in Taylor expansion in optical modulation.

In this Letter, we use a low-cost DD-MZM instead of I/Q nested MZM for optical I/Q modulation in a fiber-wireless integration system. Single polarization 20-Gbit/s QPSK signal transmission over 40-km SMF and 5-m free space at K_a -band and reception is demonstrated in this Letter. To the best of our knowledge, it is the first time to realize baseband I/Q components optical up-conversion with DD-MZM in a fiber-wireless integration system.

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