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Photonics-aided PAM-4 Wireless Transmission at 100 GHz based on Phase Insensitive Heterodyne Coherent Detection

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Abstract: We have intensively simulated PAM-4 signal transmission at 100 GHz using intensity modulation and phase-insensitive heterodyne coherent detection. This comprehensive simulation can provide significant guidance for photonics-aided THz-wave electro-optical components design.
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1. Introduction

The advent of the 5G Era, high bandwidth 4K/8K video applications, cloud services, the Internet of Things, and other broadband services are forcing operators to look for bandwidth solutions [1]. The fiber wireless integration (FWI) communication technology plays a key role to meet these demands because it combines the merits of fiber communication and wireless communication, while fiber communication has a large bandwidth capacity and wireless communication guarantees ubiquitous access [2]. In the near 6G, high-speed terahertz-wave (THz-wave, 0.1-10 THz) wireless transmission will be an inevitable trend due to the advantages of large available spectrum and good directionality of THz-wave [3-6]. Considering the bottleneck in electrical devices, photonics-assisted THz-wave generation technology is an effective solution to handle the problem of bandwidth limitation of all-electrical method [2]. In order to further improve the transmission capacity, high spectrum efficient modulation formats can be used.

For QAM signals generation, an expensive I/Q modulator, I/Q imbalance compensation and carrier recovery algorithms are required, which significantly increases the cost of the system and complexity of digital signal processing (DSP). PAM signals have amplitude information and no phase information, which can be generated by a cost-effective intensity modulator [7]. PAM-4 transmission with intensity-modulated direct-detected (IM/DD) has been investigated in metro networks and access networks [8]. However, the direct detection can only get the amplitude information of PAM with low receiver sensitivity. To mitigate channel dispersion and increase receiver sensitivity, PAM signal can be received by coherent detection and processed by simple DSP [9]. Therefore, the cost of coherent systems can be effectively reduced by combining with intensity modulated transmitter. PAM-4 signals wireless transmission at W-band with intensity modulation and coherent detection has been experimentally demonstrated [5,6]. However, it is phase-sensitivity heterodyne coherent detection and requires carrier recovery algorithm. Furthermore, these research works cannot give a comprehensive analysis of the device parameters, such as laser linewidth, digital-to-analog converter (DAC) and analog-to-digital converter (ADC) resolution, etc.

In this paper, we simulated PAM-4 signal wireless transmission at 100 GHz using intensity modulation and phase insensitive heterodyne coherent detection with comprehensive parameters of devices for different bit rates. At the transmitter side, PAM-4 intensity modulation is performed via Mach-Zehnder modulator (MZM) without using any I/Q modulators, and then heterodyne beating by two free-running lasers for 100 GHz signal generation. Since only intensity of the signal is modulated, carrier recovery is avoided, which further reduces the DSP complexity. This is the first time to intensively simulate PAM-4 THz signal wireless transmission based on intensity modulation phase insensitive heterodyne coherent detection.

2. Simulation setup

Figure 1 shows the PAM-4 THz-wave signal generation wireless transmission simulation setup based on intensity modulation and phase-insensitive heterodyne coherent detection. 5.75 Gbaud PAM-4 signals are generated by a 92 GSa/s DAC with a resolution of 8 bits, and then amplified by the electrical amplifier (EA) before driving the MZM. The MZM is biased at its quadrature point with a half-wave voltage (V_π) of 2 V. Two lasers with the same linewidth and 0.1-THz frequency spacing are used as signal light source and local oscillator (LO) at central office side and baseband unit side, respectively. The continuous wave (CW) light from external cavity laser-1 (ECL-1) is employed with the wavelength of 1553.6 nm. ECL-2 serves as a LO with an output wavelength of 1552.8 nm. One erbium doped fiber amplifier (EDFA) is used for optical signal boosting amplification before launching into the fiber. After 25 km standard single-mode fiber (SSMF) transmission, a variable optical attenuator (VOA-1) is used to control the received optical power (ROP) for sensitivity measurement. After combining with LO by an optical coupler (OC), VOA-2 is used to control the input optical power (IOP) to photodiode (PD). The PD is applied for the 0.1-THz wireless signal generation via heterodyne beating. A pair of horn antennas (HAs) is used for the wireless transmission of the signal. Note that we only consider back-to-back wireless transmission case. At the end user side, analog down conversion is performed with a 60-GHz sinusoidal RF source and a mixer. Then, the down-converted intermediate-frequency (IF) signal located at 40-GHz is boosted by another EA and captured by an 80 GSa/s oscilloscope for offline processing. Fig. 1 (a) shows the received electrical spectrum of 40-GHz IF signal. Finally, the BER can be calculated after PAM-4 demodulation based on the signal amplitude.

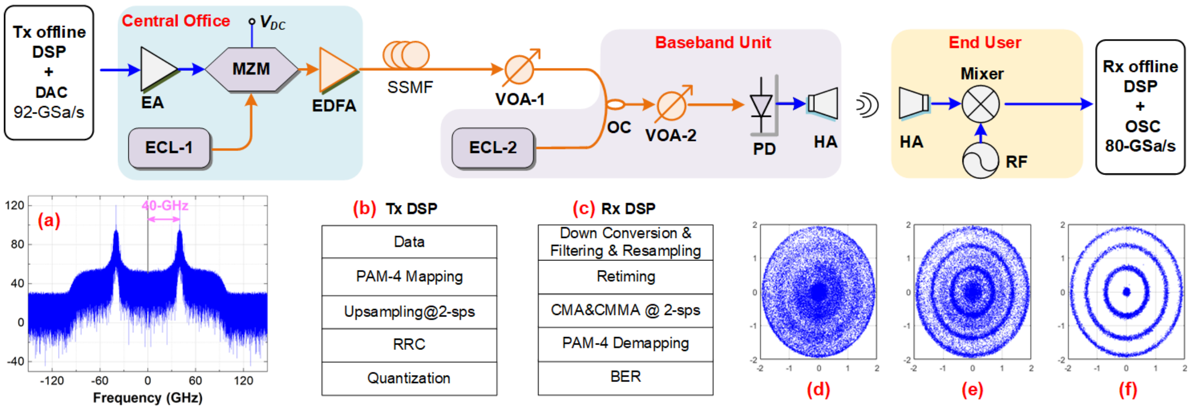

Fig.1. Simulation setup for the 100 GHz PAM-4 wireless transmission based on intensity modulation and coherent detection. (a) electrical spectrum of the received IF signal; (b) and (c) Tx and Rx offline DSP; (d) After down-sampling; (e) After retiming; (f) After equalization.

Figures 1 (b) and (c) show Tx and Rx offline DSP blocks, respectively. In the Tx offline DSP, PAM-4 symbols with a length of 2^{13} are mapped to {0,1,2,3}. After two times up-sampling, a root-raised-cosine (RRC) filter with the roll-off factor 0.4 is used to realize Nyquist pulse shaping for a 5.75 Gbaud PAM-4 signal. Then, the symbol sequence is quantized before being loaded to the DAC for digital to analog conversion. In the Rx offline DSP, the data is first down-converted to baseband signal with low-pass filtering and then resampled to 2 samples per symbol, as shown in Fig. 1(d). Then, a squaring time recovery algorithm is employed to get the best sample point, which is shown in Fig. 1(e). After clock recovery, constant-modulus-algorithm (CMA) is used for pre-convergence and cascaded multi-modulus algorithm (CMMA) with four reference circles is used for further channel equalization. After that, as shown in Fig. 1(f), the constellation can be successfully converged to four rings (the smallest ring has an amplitude close to zero), and the symbols are rotated due to laser phase noise. Since there is no phase information of the optical signal, we do not need to recover the carrier phase and each ring represents each amplitude level of the PAM-4 signal.

3. Simulation results and discussion

Figure 2 and 3 show the BER performance of PAM-4 wireless transmission at 0.1-THz versus various simulation parameters for the 2.875-, 5.75- and 11.5-Gbaud cases, including roll-off factor, linewidth, bias voltage, driving voltage, DAC and ADC resolution, ROP and IOP. A reference BER threshold of 3.8×10^{-3} is chosen. In Fig. 2(a), the BER performance under different roll-off factors for Nyquist pulse shaping in three cases is studied. Nyquist pulse shaping is an effective approach to solve the bandwidth limitation of the narrow-bandwidth devices and simultaneously to address inter-symbol interference (ISI) [8]. It is observed that the system performance is the worst with zero roll-off. Although zero roll-off can minimize the signal bandwidth, meanwhile, the signal is more susceptible to timing errors. The optimized Nyquist pulse shaping roll-off factor of 11.5-Gbaud case is found to be around 0.4 and the performance starts to deteriorate when the roll-off factor increases due to the bandwidth limitation. For 2.875- and 5.75-Gbaud cases, 0.4~1 roll-off factors all give the best performance. Therefore, the roll-off factor of 0.4 is chosen. Fig. 2(b) shows the simulated performance versus laser linewidth of ECL-1 and ECL-2 for different baud rates, respectively. The simulation results indicate that BER performance gets worse when the linewidth is up to 10^5 KHz. Here, we choose 10^4 KHz as the optimum linewidth. For PAM-4 phase-insensitive coherent detection, the BER performance versus the bias voltage and driving voltage of MZM is investigated. When V_π is set to 2-V, the BER performance is the best on the condition that the bias voltage and driving voltage is 1V and 0.26V, as shown in Fig. 2(c) and (d). When the bias voltage deviates from 1 V and keep the driving voltage unchanged, BER performance begins to deteriorate sharply due to nonlinearity character of MZM. Therefore, the bias voltage and driving voltage are interacted on each other.

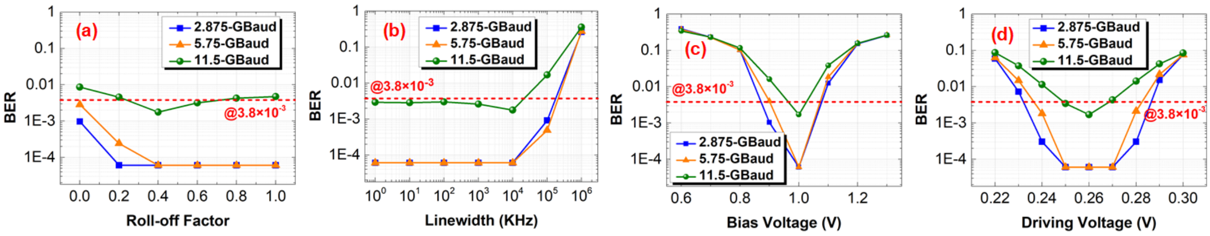

Fig.2. (a) BER versus the roll-off factor of Nyquist pulse shaping. (b) BER versus the laser linewidth. (c) BER versus the bias voltage of MZM. (d) BER versus the driving voltage of MZM.

A 2-bit DAC is not enough to generate a PAM-4 signal because pulse shaping is used at the transmitter. From Fig. 3(a), it can be found that 3-bit DAC resolution is enough to achieve below 3.8×10^{-3} threshold and the curves become stable when the DAC resolution increases on the condition of 0.4 roll-off factor for three baud rate cases. Fig. 3(b) indicates the similar trend of BER performance versus ADC resolution as Fig. 3(a). The BER performance versus different ROP referring to the optical power before coupling with LO to measure the simulated receiver power sensitivity is tested, as shown in Fig. 3(c). Increasing the ROP after the fiber is an effective way to further improve BER performance. It can be noted that 6.5 and 3.5 dB sensitivity is achieved in 2.875 and 5.75 Gbaud cases to achieve BER below 3.8×10^{-3} compared with 11.5 Gbaud case, respectively. Finally, the BER performance versus the IOP, which refers to the optical power before entering the PD, is given in Fig. 3(d). One can note that the sensitivity gain of 5 and 3 dB are obtained in 2.875 and 5.75 Gbaud cases to achieve BER below the reference threshold compared with 11.5 Gbaud case at the same ROP.

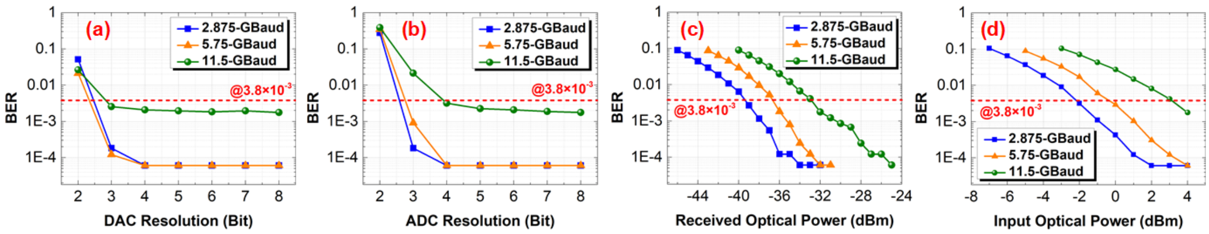

Fig.3. (a) BER versus the DAC resolution. (b) BER versus the ADC resolution. (c) BER versus the ROP. (d) BER versus the IOP.

4. Conclusions

We have comprehensively simulated 2.875-, 5.75- and 11.5-Gbaud PAM-4 signals wireless transmission at 100 GHz based on intensity modulation and phase-insensitive heterodyne coherent detection. An intensive comparison of performance versus various parameters operating at different bit rates was discussed, including roll-off factor, linewidth, bias voltage, driving voltage, DAC and ADC resolution, ROP and IOP. This comprehensive simulation of PAM-4 signal wireless transmission based on phase-insensitive heterodyne coherent detection can provide significant guidance for photonics-aided THz-wave electro-optical components design.

5. References

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