40-GHz Bandwidth Envelope Detector Used in 0.3-THz IM/DD System for 4096-QAM DSM Signal Transmission

Jianyu Long[1], Jingwen Tan[1], Jianjun Yu[1,2*], Jiaxuan Liu[1], Xiongwei Yang[1], Yi Wei[1], Kaihui Wang[1], Wen Zhou[1], Xianmin Zhao[3], Junjie Ding[2], Jiao Zhang[2], Min Zhu[2], Jianguo Yu[4], and Feng Zhao[5]

[1]*Fudan University, Shanghai, 200433, China * jianjun@fudan.edu.cn*
[2]*Purple Mountain Laboratories, Nanjing, 211111, China*
[3]*China Harbin Institute of Technology, Harbin, 100051, China*
[4]*Beijing University of Posts and Telecommunications, Beijing, 100876, China*
[5]*Xi'an University of Posts and Telecommunications, Xi'an, 710121, China*

Abstract: We experimentally demonstrate a photonics-aided THz IM/DD transmission system using a large-bandwidth envelope detector and delta-sigma modulation. The proposed system can support 4096-QAM DSM modulation and simple and low-cost receiver architecture.

1. Introduction

The Terahertz (THz) band, as an underutilized spectrum, shows promising potential in high-speed wireless communication system like THz-over-fiber (ToF) by offering a significant bandwidth[1]–[4]. In Ref [5], [6], up to 850-m and 480-Gbps THz transmission show the feasibility of THz high-speed transmission. However, existing THz systems or ToF systems are mostly based on coherent schemes that are costly and complex[7]. With envelope detector, THz IM/DD scheme can avoid high-cost and complex devices like high-speed THz mixers, high-frequency local oscillators, and gets a simple Rx DSP process without polarization de-multiplexing and frequency offset and phase recovery[8], [9]. Yet, a typical wireless signal envelope detector usually possesses a limited bandwidth, which cannot fully exploit the wide bandwidth offered by THz band. Besides, envelope detectors that perform square-law detection are prone to saturate and will cause distortion among levels for multi-level PAM or QAM signals. To address these issues, we use a large bandwidth (6-dB bandwidth >40-GHz) envelope detector and utilize the delta-sigma modulation (DSM). Apart from improving the signal-to-noise-ratio (SNR) and reduce the signal quantization noise, DSM requires analog-to-digital converters (ADCs) with only 1 bit to avoid the influence of saturation effect and further reduce costs[10]. Still, the over-sampling process in DSM will substantially decrease the system capacity. Here we modulate the high-order multi-level QAM signals into 1-bit DSM-OOK format with the lowest possible over-sampling ratio to not only avoid the system capacity reduction cause by over-sampling, but also improving the SNR.

In this paper, we propose and demonstrate a large-bandwidth THz IM/DD system with a > 40-GHz bandwidth envelope detector using DSM. With photonics-aided method, 2048-QAM ~ 4096-QAM signals are quantized into 1-bit up-to-40-GBaud DSM-OOK signals for 0.3-THz 1-m wireless transmission. Based on the experimental results, the BER of the high-order-QAM DSM signals received from the envelope detector can all satisfy the 20% SD-FEC threshold of 2.4×10^{-2}.

2. Principles and Experimental Setup

Fig. 1 shows the schematic of the THz communication system using DSM in IM/DD channel device. Fig. 1 (a) and (b) give the photos of the transmission link, transmitter and receiver. At the Tx side, the baseband electric signal, amplified by the electric amplifier (EA) and delivered by the 64-GSa/s arbitrary waveform generator (AWG), is modulated via the intensity modulator (IM). Two external cavity lasers (ECLs) with the power of 14.5 dBm produce CW light waves at 193.2-THz and 193.5-THz. After the two laser beams are combined by polarization maintaining optical coupler (PM-OC), they are sent to the IM as an optical carrier. The coupled signal with 4.5 dBm optical power is amplified by a polarization-maintaining erbium-doped fiber amplifier (PM-EDFA), and the output optical power after PM-EDFA is 11.3 dBm. Heterodyne beaten by the uni-traveling-carrier photodiode (UTC-PD), the wireless 0.3-THz signal is transmitted into free space.

As shown in Fig. 1 (c), the baseband high-order modulated DSM digital signal at the transmitter is firstly offline generated via PRBS sequence generation and QAM mapping. Next, the baseband 2048-QAM signal and 4096-QAM signal are I/Q interleaved, up-sampled, filtered via a RC filter and quantized using a 1-bit fourth-order DSM with an OSR of 10. The zero-poles and magnitude-frequency response for the 1-bit DSM are presented in Fig. 1 (i) and (ii). It shows the noise transfer function (NTF) of the DSM, which can represent its noise shaping performance. We can see that the quantization noise of the signal is pushed into the high frequency part and the quantization noise of the baseband part is suppressed. Fig. 1 (iii) shows the spectrum of the signal after DSM. Up to 40-GBaud DSM-OOK signals are resampled to 64-GSa/s for AWG to send.

A pair of polytetrafluoroethylene (PTFE) lenses (ie, lenses with 10-cm diameter and 20-cm diameter focal length) are deployed for the signal beam aggregation to support a 1-m wireless transmission link. Meanwhile, the transmission of the wireless THz wave requires strict beam alignment. Through 1-m wireless transmission, signal is amplified by lens2, a waveguide antenna (WA) and a THz-band low-noise amplifier (LNA, 250GHz-350GHz) at the receiving end, and the THz signal is down-converted to a baseband OOK signal through an envelope detector. The signal is amplified by two EAs and then captured by a real-time oscilloscope (OSC) with a sampling rate of 64-GSa/s.

As shown in Fig. 1 (d), the DSP in the receiver includes two parts: the OOK demodulation and the DSM demodulation. The signal is firstly resampled into 2 Sa/symbol and then processed by a 51-tap-T/2-spaced constant modulus algorithm (CMA) equalization, and a 151-tap decision-directed least mean square (DD-LMS) equalizer is adopted to further improve BER performance. Thanks to DSM, only traditional DSP processing with a low complexity is required. Before DSM demodulation, the equalized signal is decided into the standard OOK level. After resampling, root raised cosine filtering, low-pass filtering, I/Q de-interleaving and QAM signal decision, the baseband 4096-QAM signal can be recovered.

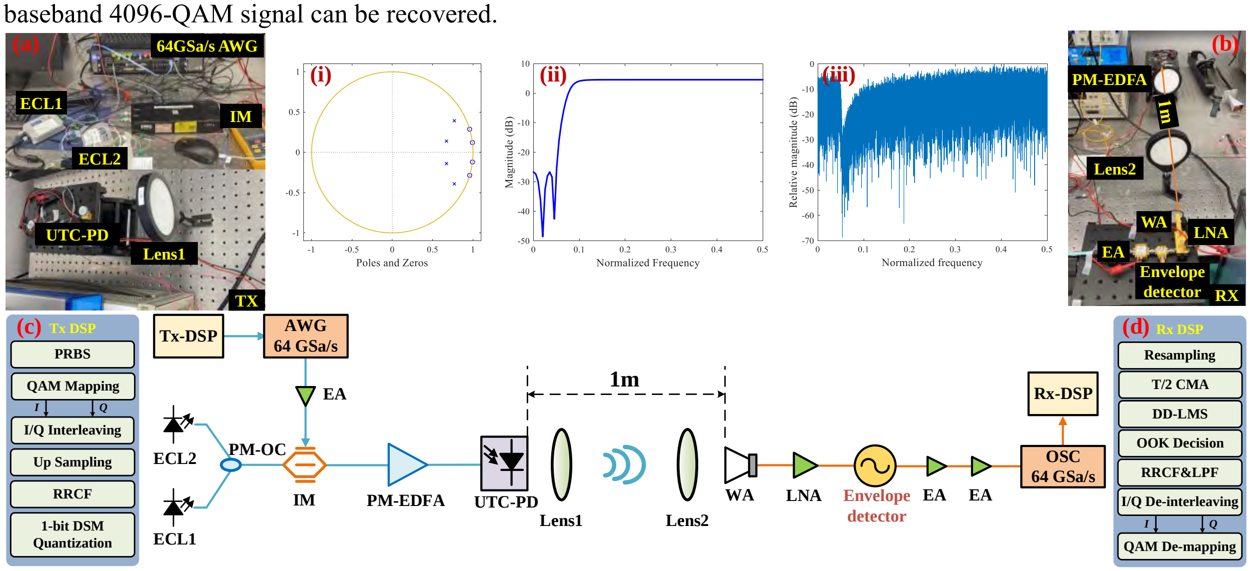

Fig. 1. Experimental setup of the THz communication system using DSM in IM/DD channel. Photos of (a) transmitter; (b) transmission link and receiver. (c) Tx DSP; (d) Rx DSP.

3. Results and discussion

The performance of DSM-OOK signals has a great impact on the recovery of ultra-high-order QAM signals. Fig. 2 (a) shows the relationship between the BER of the recovered high-order QAM and the BER of the OOK signal after DSM. It can be seen that if the BER of DSM-OOK is low enough, the performance of high-order QAM signals will tend to be stable. When the BER of the DSM-OOK is less than 3.92×10^{-4}, the BER of 4096-QAM satisfies the 20% SD-FEC threshold of 2.4×10^{-2}. Fig. 2 (b) shows the measured BER of the 40-GBaud DSM-OOK signals with different optical power into UTC-PD. In back-to-back and 1-m wireless transmission cases, the 40-Gbaud DSM-OOK signals can satisfy the 3.9×10^{-4} threshold when the optical power is larger than 7.0 and 12.0 dBm. Fig. 2 (c) presents the measured BER of DSM-OOK signals with different baud rate in BTB case and 1-m wireless case. It can be seen that when the optical power is 13.3 dBm, the BER of the 4096-QAM signal recovered after 1-m wireless transmission of the DSM-OOK signal is within the 20% SD-FEC threshold of 2.4×10^{-2}. Moreover, its BER performance closely matches that of the BTB case at 10.3-dBm optical power. In the 5.7-dBm scenario, the BER performance in the BTB configuration follows the same trend as its 10.3-dBm counterpart, while the performance at 1 meter deteriorates with a distinct, less consistent trend compared to the other cases. the BER. Fig. 2 (d) shows the spectrum of the received baseband signal after 1-m wireless transmission. Through wireless channel transmission, the signal quality deteriorates, but the SNR of the baseband signal remains above 15 dB, which ensures the reliability of signal demodulation. Fig. 2 (i) and (ii) show the constellation diagrams of recovered 2048-QAM and 4096-QAM signals in the 40-GBuad 1-m wireless scenario, respectively. For THz communication system using DSM in IM/DD channel, the line bit rate is $40\times\log_2(4096)/2/10/(1+20\%)=20$ Gbit/s.

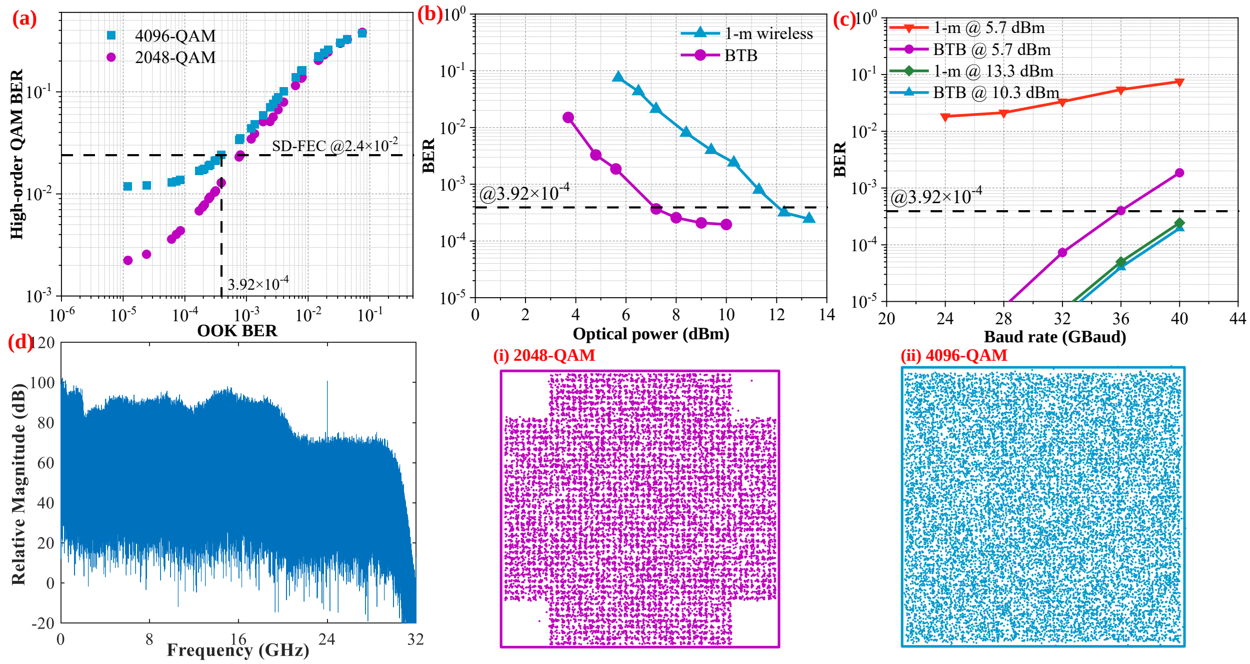

Fig. 2. The experimental results. (a) BER curves of the recovered high-order QAM versus the BER of the DSM-OOK signals; Measured BER of the DSM-OOK with (b) different optical power and (c) different baud rate; (d) Spectrum of the received baseband signal after 1-m wireless transmission; Constellations of the recovered (i) 2048-QAM and (ii) 4096-QAM.

4. Conclusions

We experimentally demonstrate a large-bandwidth photonics-aided THz transmission system with envelope detection and DSM. With such system, up to 4096-QAM DSM signal can be successfully transmitted at 0.3-THz over 1-m wireless link with a net rate of 20 Gbit/s. The BER of the 4096-QAM after 1-m wireless transmission can satisfy the 20% SD-FEC threshold of 2.4×10^{-2}. The proposed scheme provides a cost-controllable and promising candidate for THz transmission of high-order QAM.

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5. References

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