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Research article

Investigation on the performance of photonics-aided W-band millimeter-wave wireless transmission

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A B S T R A C T

W-band (75–110 GHz) is a potential radio frequency band to provide long-distance wireless links for mobile data transmission. This paper proposes and experimentally demonstrates high-speed wireless transmission at W-band using photonics-aided method, including optical heterodyne, photonics-aided down-conversion without RF oscillator and coherent detection. A comparison between the photonics-aided method and the conventional electronic method employing solid-state electronic devices is conducted for the first time. The photonics-aided method is shown to offer advantages such as lower harmonic components, spur, reduced nonlinearity, and no local oscillator leakage, results in a 2.5 dB better performance of the photonic-aided W-band mm-wave transmitter compared to the electronic one. In the terms of receiver, the photonics-aided method can surpass the electronic method, with the help of larger electro-optical modulator bandwidth and lower drive voltage in the photonic down-conversion stage. Ultimately, using the photonics-aided method, a recorded equivalent transmission distance of 29 km@84 GHz and 45km@75.6GHz is achieved respectively for 1Gbaud QPSK signal.

1. Introduction

The demands of wireless communication capacity are increasing with the development of applications in military, internet of thing, and unmanned technology, etc. W-band (75–110 GHz) millimeter-wave (mm-wave) communication has the potential of large bandwidth, high reliability and high security [1–6]. A conventional way to generate and receive W-band mm-wave signal is based on solid state electronic devices. The bandwidth bottleneck of electronic devices limits its applications in ultra-wide band frequency mixing, signal modulation and demodulation. Microwave photonics technique becomes an alternative solution for wide-band W-band frequency up-conversion, down-conversion and long-distance data delivery applications [7–20]. Using the combination of photonics-aided mm-wave up-conversion module and electronic mixer based down-conversion module, Ref [12] demonstrates a 60-Gbps wireless link over 1.2 m at 81 GHz, Ref [14] demonstrates a 132-Gbps 3 × 3 MIMO communication system over 0.1 m wireless link at 88 GHz. Nowadays, the photonic-aided RF (radio frequency) down-conversion and demodulation, is also attracted much attention, which benefits from the large bandwidth, lower harmonic component and no need for local oscillator. Ref [15] demonstrates a 4 GHz-bandwidth seamless fiber-wireless system in W-band using optical phase modulation and self-homodyne. For long distance mm-wave communication application such as information delivery over land, sea and sky, the received power of mm-wave signal at the receiver is weak, the power efficiency at the transmitter side and the sensitivity at the receiver side are very important, and it is valuable to find a better solution with lower detection sensitivity that supports longer transmission distance and larger data rate with the commercial photonics and electronic devices.

In this paper, we propose and experimentally demonstrate a photonic-aided W-band mm-wave transmission system based on optical heterodyne, photonic-aided down-conversion without RF oscillator and coherent detection. The longest equivalent

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transmission distance is explored and the performance of both photonics-aided and electronic methods is investigated experimentally. This is the first time to explore the extreme performance of photonics-aided W-band mm-wave transmission system and perform a comparison between photonics-aided and electronic methods employing commercial solid state electronic devices.

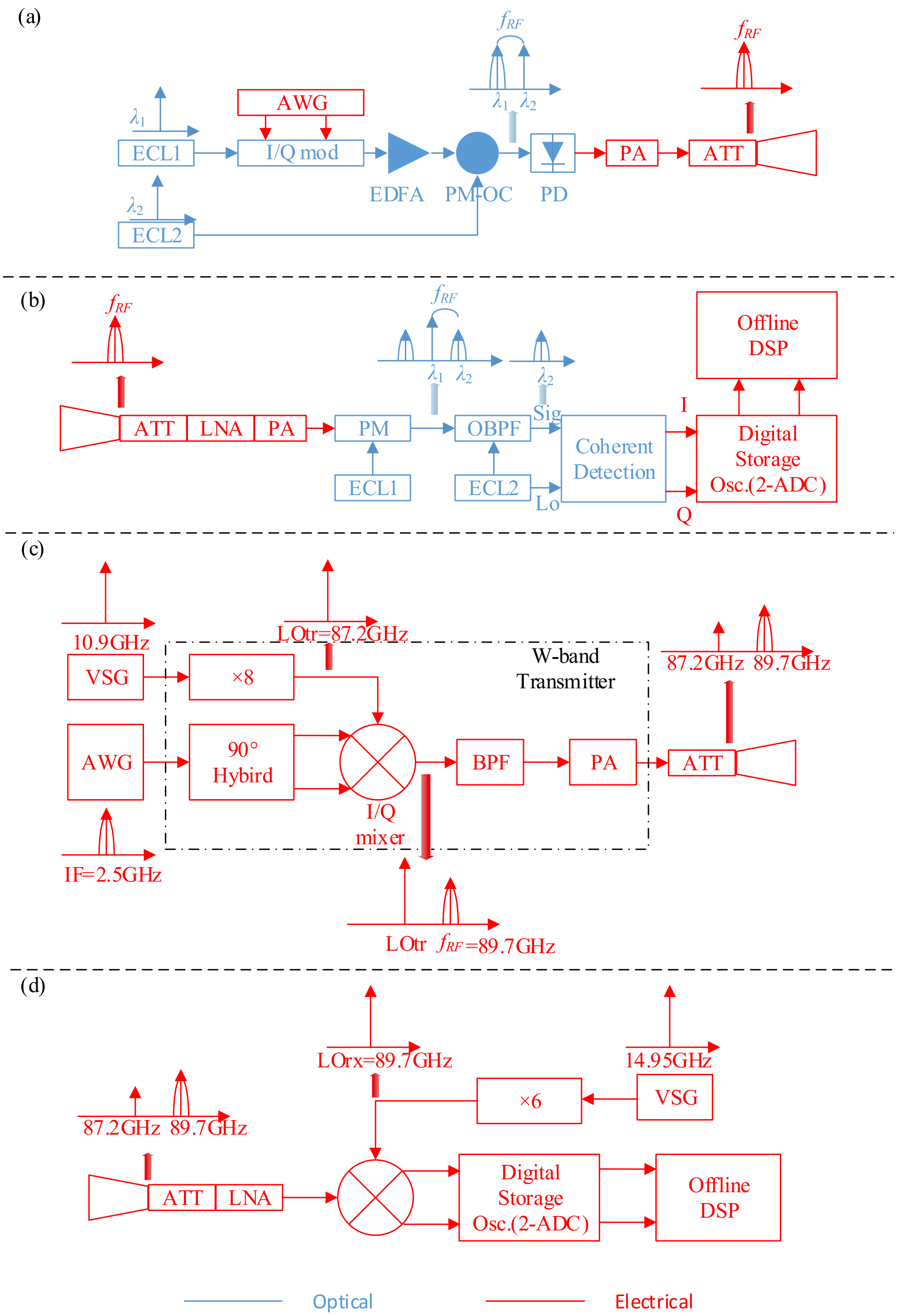

Fig. 1. Schematic diagram of the W-band transmission system using different methods, (a) OT: photonics-aided transmitter, (b) OR: photonics-aided receiver, (c) ET: electric transmitter, (d) ER: electric receiver.

2. Principle

The schematic diagrams of the W-band mm-wave system with photonics-aided and electronic methods are shown in Fig. 1, and the optical and electrical spectrum for both methods are presented. For the photonics-aided transmitter (OT), as shown in Fig. 1(a), optical heterodyne method is used to generate mm-wave. A lightwave with the wavelength at λ_1 is modulated by electrical QPSK/QAM16 signal through an optical I/Q modulator. Then the modulated optical signal is amplified by an Erbium-doped fiber amplifier (EDFA) and coupled with another lightwave with the wavelength at λ_2 at a polarization maintaining optical coupler (PM-OC). The frequency interval between two optical signals is f_{RF}, which is corresponding to the frequency of W-band mm-wave. Optical heterodyne is performed at the high-speed photo detector (PD) to generate electrical mm-wave signal. Finally RF mm-wave signal is amplified by W-band electrical power amplifier (PA).

The electronic transmitter (ET) is shown in Fig. 1(c), QPSK/QAM16 signal is modulated to a 2.5 GHz intermediate frequency (IF) firstly, and then up-converted to W-band at the frequency of f_{RF} through single sideband modulation (SSB). An 8 times frequency

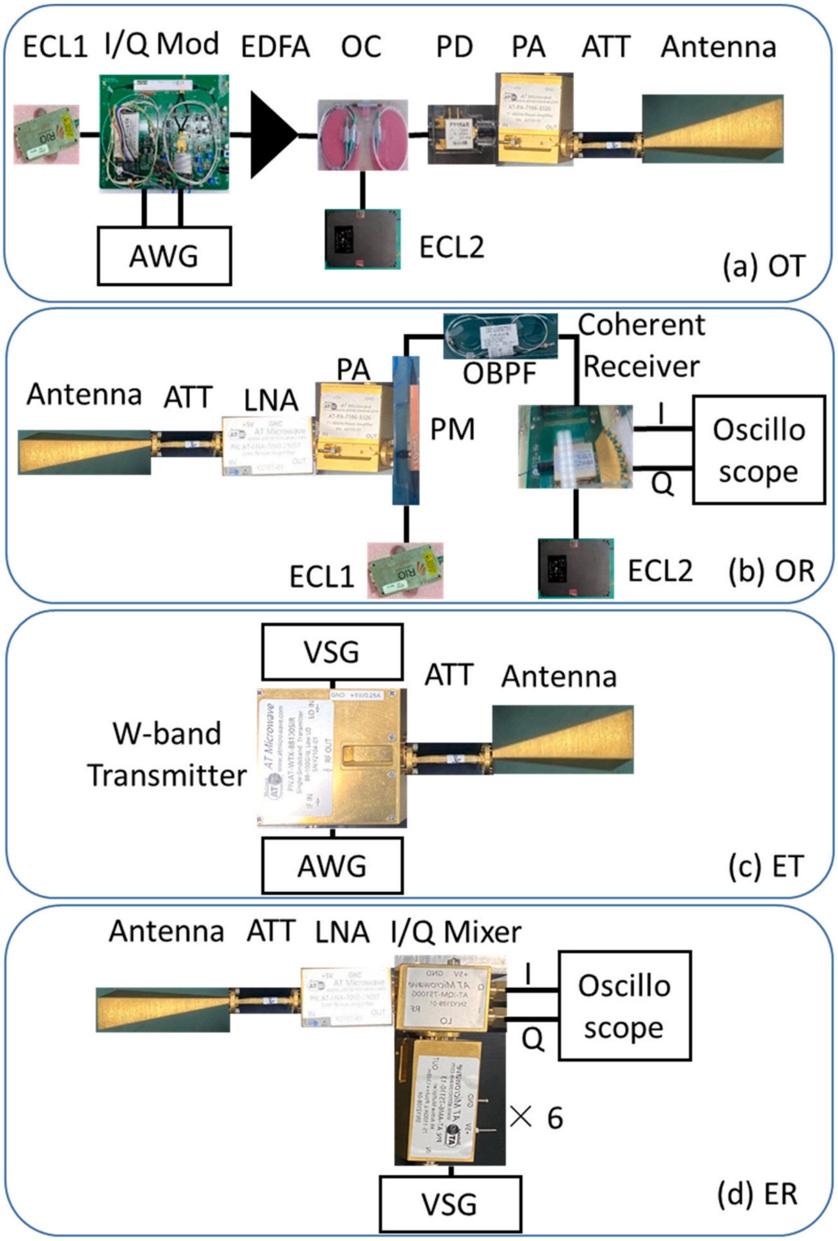

Fig. 2. Experiment setup for the proposed W-band wireless transmission systems. (a) OT: photonics-aided transmitter, (b) OR: photonics-aided receiver, (c) ET: electric transmitter, (d) ER: electric receiver.

multiplier is employed to obtain 87.2 GHz local oscillator (LO_{tr}), so the generated RF frequency is 89.7 GHz (10.9 GHz × 8 + 2.5 GHz). In order to eliminate the influence of LO leakage, the modulated mm-wave signal passes through a band-pass filter before being amplified. For both OT and ET, the mm-wave signal is attenuated and injected into a horn antenna for wireless transmission.

The photonics-aided receiver (OR) is shown in Fig. 1(b), the wireless signal is received by the horn antenna, then attenuated and amplified with low noise amplifier and power amplifier before driving optical phase modulator. Microwave photonic frequency down-conversion without RF oscillator and coherent detection are used to increase the sensitivity of the receiver [18].

The electronic receiver (ER) is shown in Fig. 1(d), the wireless signal received by the antenna is attenuated and amplified, which is the same as OR. A 6-times frequency multiplier is employed to obtain an 89.7 GHz local oscillator (LO_{rx}), which is used for homodyne detection through an electrical I/Q mixer.

The output signal of both OR and ER are sampled and stored. An offline digital signal processing (DSP) is performed with frequency offset tracking, channel estimation, carrier phase recovery. Finally, bit error rate is calculated over 10ˆ6 bits.

ECL, external cavity laser; BPF: band pass filter; LNA, low noise amplifier; PA, power amplifier; PM-OC, polarization maintaining optical coupler; OBPF, optical band-pass filter; ATT: attenuator;

PM: phase modulator; VSG: vector signal generator.

3. Experiment setup and results

3.1. Experiment setup

OT-OR, OT-ER, and ET-ER mm-wave transmission systems are established to investigate the performance of high-speed wireless transmission link at W-band respectively. We experimentally demonstrate 1.25 m wireless transmission with 1 Gbaud QPSK/QAM16 signal. Fig. 2 shows the experiment setup for the proposed W-band wireless transmission systems.

For the OT module, the CW lightwave from an external cavity laser (ECL1, 10 dBm) at 1550.12 nm with polarization maintaining pigtail is injected into an optical I/Q modulator, which is driven by 1 Gbaud QPSK/QAM16 signal generated from an arbitrary waveform generator (AWG, TEK-AWG70002B). Then, the signal carrier with QPSK/QAM16 signal is amplified to 10 dBm by Erbium-doped fiber amplifier (EDFA) with over 30 dB gain, and coupled with an optical LO lightwave of 10 dBm before optical heterodyne. Limited by the bandwidth of W-band power amplifier (71–86 GHz), the wavelength of optical LO from ECL2 is 84 GHz frequency offset to the wavelength of ECL1. Both ECLs run freely with a linewidth less than 20 kHz and frequency shift less than 50 MHz@1 h. A photo-detector (Finisar, XPDV4120) with 3-dB bandwidth of 90 GHz is used to realize photo-to-electric conversion.

For the ET module, a commercial integrated W-band transmitter (AT-WTX-88100SIR) is used, IF (2.5 GHz) carrying 1 Gbaud QPSK/QAM16 signal is generated from AWG. A single tone signal of 10 dBm at 10.9 GHz is multiplied by 8 times for frequency mixing, so the generated RF frequency is 89.7 GHz (10.9 GHz × 8 times +2.5 GHz) after single sideband modulation using a 90° hybrid.

The mm-wave signal is sent out and received by a pair of horn antennas with 25-dBi gain, and several attenuators are employed before transmitter horn antenna and after receiver horn antenna for equivalent long transmission.

For the OR module, the received mm-wave signal is modulated using a phase modulator (EOspace, Bandwidth = 65 GHz@6 dB), and the upper sideband of PM output is sent to a coherent receiver (Fujitsu, ICR-100-EVK) for homodyne coherent detection. The power of the lightwave injected into the phase modulator is 7 dBm. And the power of the LO for coherent detection is 2 dBm. For the ER module, a 14.95 GHz single tone of 3 dBm is multiplied by 6 times through a multiplier (AT-AM6-75110-13) to obtain an 89.7 GHz LO_{rx}, then the LO_{rx} is injected into an IQ mixer (AT-IQM-75110G) for homodyne detection. The output IQ data of optical coherent detector and electronic mixer is sampled and stored by a high-speed oscilloscope (TEK-MOS64B) for offline DSP.

3.2. Results

The nonlinearity of OT-ER, OT-OR, and ET-ER systems is investigated by employing 1 Gbaud QAM16 signal. To optimize the

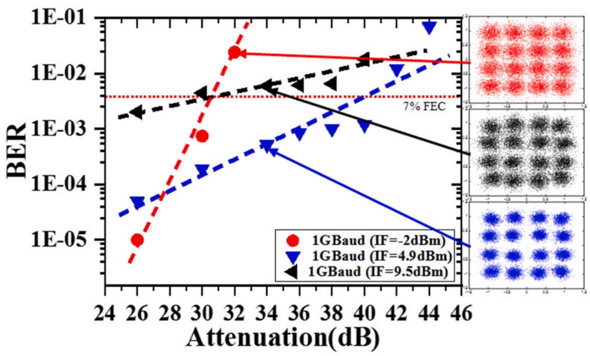

Fig. 3. BER curve of QAM16 mm-wave signal with different input IF power and Constellations after DSP: ET-ER while IF power equals −2, 4.9 and 9.5dBm.

performance of the ET module in the integrated W-band transmitter, the input IF power is adjusted considering the nonlinearity of the electronic amplifier. Digital predistortion (DPD) method is applied for each scenario with varying IF power levels. The BER curve and constellations with different input IF power is illustrated in Fig. 3. The constellations reveal that insufficient transmitted power occurs at an IF power of −2 dBm, while more noise is generated at 9.5 dBm, indicating amplifier saturation in the transmitter. The optimal input IF power tradeoff is found to be 4.9 dBm, resulting in the best performance for QAM16 signal transmission, as depicted in Fig. 3.

The measured transmitted power is 11 dBm, while the input IF power is 4.9 dBm. The optical input power injected into PD is adjusted to achieve the same output RF power to the ET module. The frequency spectrums of generated W-band mm-wave after 32 dB attenuation with ET and OT are shown in Fig. 4(a) and (b), respectively. It is indicated that the photonics-aided method has the advantage of lower harmonic component, spur, reduced nonlinearity and no local oscillator leakage, comparing to the conventional electronic method.

Fig. 5 indicates the BER of 1 Gbaud QAM16 mm-wave signal versus the RF attenuation for OT-ER, OT-OR, and ET-ER systems. The best performance of the OT-ER, OT-OR, and ET-ER systems is 43 dB, 40.5 dB and 40.5 dB RF attenuation for 1 Gbaud QAM16 signal. The OT module shows about 2.5 dB better performance than the ET module, which coincide with the frequency spectrum result in

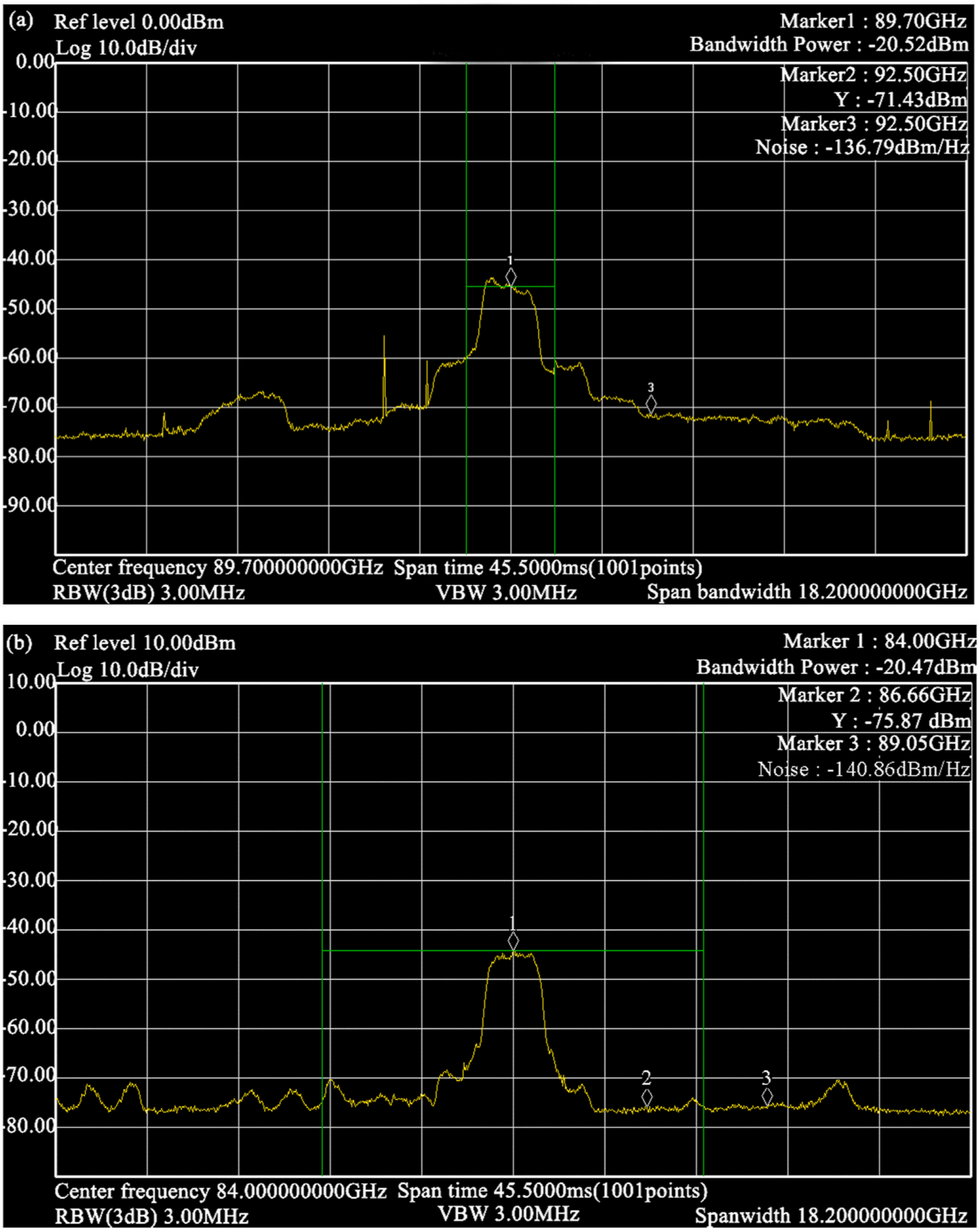

Fig. 4. The frequency spectrum of generated W-band mm-wave after 32 dB attenuation with (a) ET, (b) OT.

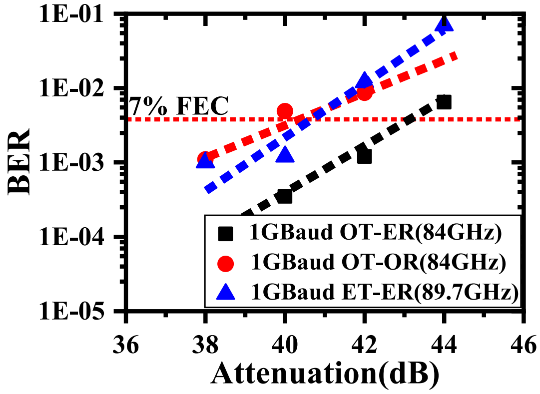

Fig. 5. BER curve of QAM16 mm-wave signal versus attenuation.

Fig. 4. The BER performance of OR module is worse compared to that of ER module when attenuation is low. The reason could be that the phase modulator of OR module introduces more noise at higher power levels.

Since the sensitivity of the OR module is limited by the frequency response of the photoelectric devices such as the phase modulator, the OR module does not have an ideal performance at 84 GHz as the ER module does. As mentioned in the Experiment Setup part before, the 6-dB bandwidth of our phase modulator is 65 GHz. Fig. 6 shows the frequency spectrum of the sampled 1 Gbaud QAM16 signal after 40 dB attenuation using ER and OR module. Spectrum fading can be observed obviously using the OR module.

In order to investigate the influence caused by the phase modulator, another set of experiment is employed at 75.6 GHz using OT-OR system. Due to the higher frequency response of the PD at 75.6 GHz, the optical power injected into PD is adjusted to obtain the 11 dBm transmitted RF power. The BER curve of QAM16 mm-wave signal versus RF attenuation for OT-OR systems at 75.6 GHz and 84 GHz is shown in Fig. 7. The best performance of the OT-OR for 1 Gbaud QAM16 signal delivery at 75.6 GHz has 7 dB improvement than at 84 GHz. Therefore, it is reasonable to believe that the OR module could reach better performance using photoelectric phase modulator with larger bandwidth.

The maximum delivery distance of the OT-OR system is investigated, the experiment of QPSK signal delivery is conducted at 75.6 GHz and 84 GHz using OT-OR system. The transmitted RF power is 14.5dBm. Fig. 8 indicates the BER of 1 Gbaud QPSK mm-wave signal versus the RF attenuation for OT-OR systems. Considering the BER below 7 % FEC threshold of 3.8×10^{-3}, the best performance is 56 dB and 47 dB RF attenuation for 1 Gbaud QPSK signal at 75.6 GHz and 84 GHz, respectively.

Taking atmospheric loss in consideration, the received power P_R of proposed OT-OR system can be given by

$$P_R(dBm) = P_T + G_T + G_R - 20\log(4\pi d / \lambda) - A - L_A \times d$$

Where P_T is the transmitted power 14.5 dBm, λ is the wavelength of the mm-wave, d is the wireless transmission distance 1.25 m, the term $20\log(4\pi d / \lambda)$ is the free-space transmission loss, G_T and G_R are the gain of the transmitting and receiving antenna, which are

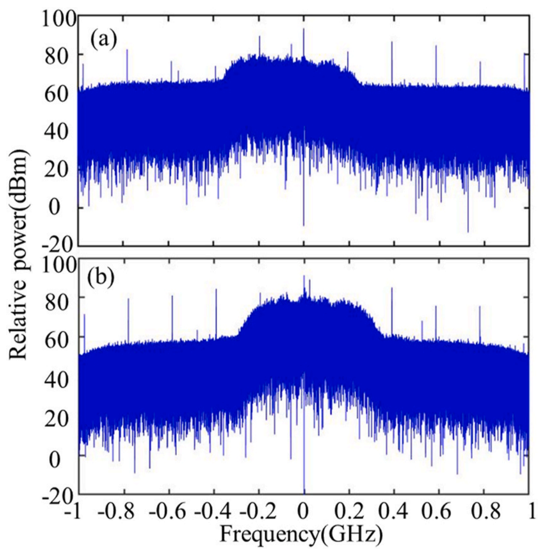

Fig. 6. Frequency spectrum of the sampled 1Gbaud QAM16 signal after 40 dB attenuation using (a) ER, (b) OR.

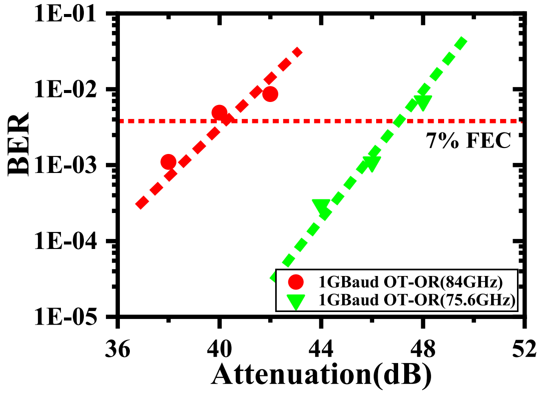

Fig. 7. BER curve of 1 Gbaud QAM16 mm-wave signal versus RF attenuation for OT-OR systems at 75.6 GHz and 84 GHz.

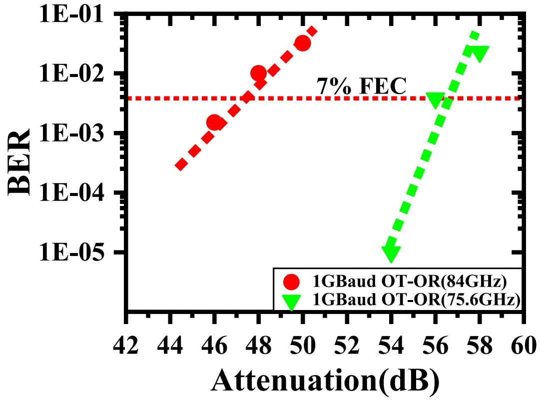

Fig. 8. BER curve of 1 Gbaud QPSK mm-wave signal versus RF attenuation for OT-OR systems at 75.6 GHz and 84 GHz.

both 25 dBi, A is RF attenuation, L_A is the atmospheric loss factor. According to the file "*Attenuation by atmospheric gases and related effects*" (ITU-R P.676-12) provided by the International Telecommunication Union, the approximant calculation value of L_A is 0.363 dB/km and 0.376 dB/km and at 75.6 GHz and 84 GHz while the temperature is 300 K, the water vapour density is 7.5 g/m^3 and the pressure is 1013.25 hPa.

Since the best performance of the OT-OR system is 56 dB and 47 dB attenuation for 1 Gbaud QPSK signal at 75.6 GHz and 84 GHz, the detection sensitivity of the OR module at 75.6 GHz and 84 GHz is −63.46 dBm and −55.37 dBm, respectively. Parameters taken from the datasheet of electronic amplifier and antenna in stock are used as equivalent conditions. Since the output power of the PA can reach 26 dBm and the antennas can be replaced to the Cassegrain antennas with 45-dBi gain, as shown in Fig. 9 (a) and (b). The proposed OT-OR system could support as long as 45 km and 29 km wireless atmospheric transmission for 1 Gbaud QPSK signal at 75.6 GHz and 84 GHz, respectively. Using the results in Fig. 5, the maximum delivery distance of QAM16 is also is investigated. The equivalent atmospheric transmission conditions are summarized in Table I. A new unit of measurement, Distance·Bitrate (km·Gbps), is utilized to assess the system's performance. It is demonstrated that the OT-OR system can achieve a maximum of 100 km·Gaps via QM16.

4. Conclusion

In this paper, we present a photonic-aided W-band mm-wave transmission method based on optical heterodyne, photonic-aided down-conversion without RF oscillator and coherent detection. The performance of electrical method using commercial devices is investigated. The photonic-aided W-band mm-wave transmitter demonstrates 2.5 dB superior performance compared to the electronic one due to lower harmonic component, reduced nonlinearity, and absence of local oscillator leakage. Additionally, the photonics-aided receiver can surpass the electronic one with the assistance of a wider electro-optical modulator bandwidth in the photonic down-conversion section. A recorded equivalent wireless atmospheric transmission of 45 km and 29 km for a 1 Gbaud QPSK signal at 75.6 GHz and 84 GHz is achieved. We are confident that the proposed photonics-aided system can facilitate wireless W-band mm-wave transmission with increased capacity and extended distances, offering broad prospects for applications in ultra-wide-band and ultra-high-speed transmission.

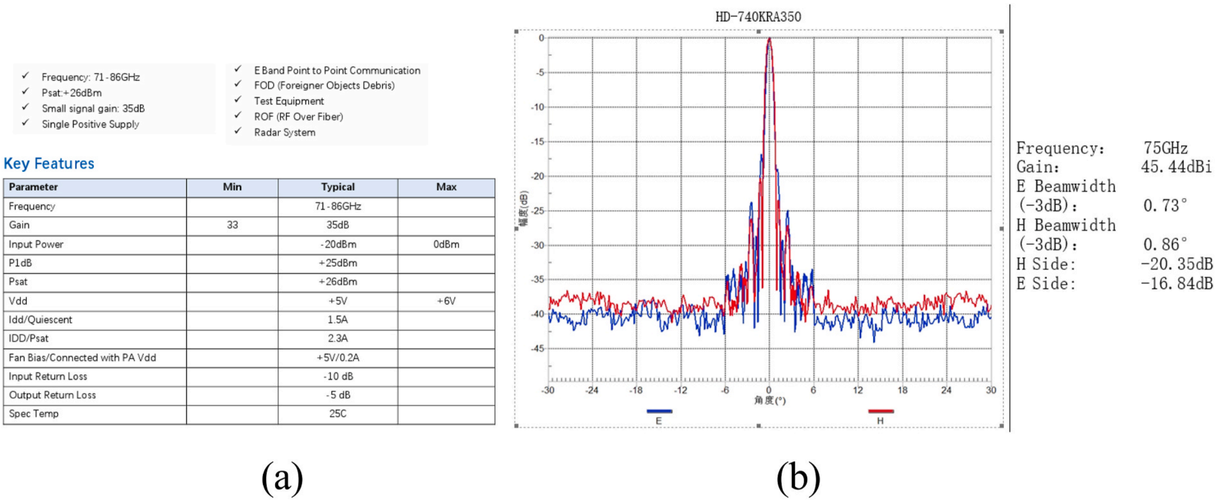

Fig. 9. Parameters taken from the datasheet of (a) electronic amplifier and (b) antenna in stock.

Table 1
Maximum transmission calculation.

Experiment conditions	75.6 GHz, OT-OR ($L_A = 0.363dB/km$) 1Gbaud QPSK		84 GHz, OT-OR ($L_A = 0.376dB/km$) 1Gbaud QPSK		84 GHz, OT-OR ($L_A = 0.376dB/km$) 1Gbaud QAM16		89.7 GHz, ET-ER ($L_A = 0.382dB/km$) 1Gbaud QAM16	
	This paper (1.25 m)	Equivalent conditions (45 km)	This paper (1.25 m)	Equivalent conditions (29 km)	This paper (1.25 m)	Equivalent conditions (25 km)	This paper (1.25 m)	Equivalent conditions (24.8 km)
P_T (dBm)	14.5	26	14.5	26	11	26	11	26
G_T (dBi)	25	45	25	45	25	45	25	45
G_R (dBi)	25	45	25	45	25	45	25	45
$20\log(4\pi d/\lambda)$ (dB)	71.96	163.08	72.87	160.18	72.87	158.89	73.44	159.39
A(dB)	56	/	47	/	40.5	/	40.5	/
$L_A \times d$ (dB)	/	16.34	/	10.90	/	9.40	/	9.47
P_R (dBm)	−63.46	−63.42	−55.37	−55.08	−52.37	−52.29	−52.89	−52.86
Distance·Bitrate (km·Gbps)	90		58		100		99.2	

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Data availability statement

Data associated with this study has not been deposited into a publicly available repository.

CRediT authorship contribution statement

Li Tao: Conceptualization. **Qichao Lu:** Writing – review & editing, Writing – original draft, Investigation. **Renjie Li:** Supervision. **Zhili Wang:** Data curation. **Tong Cheng:** Data curation. **Ying Yu:** Formal analysis. **Wei Huang:** Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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