A 220 GHz Frequency-Division Multiplexing Wireless Link with High Data Rate

ZHANG Bo[1], WANG Yihui[1], FENG Yinian[1],
YANG Yonghui[2,3], PENG Lin[2,3]
(1. University of Electronic Science and Technology of China, Chengdu 610054, China;
2. ZTE Corporation, Shenzhen 518057, China;
3. State Key Laboratory of Mobile Network and Mobile Multimedia Technology, Shenzhen 518055, China)

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Abstract: With the development of wireless communication, the 6G mobile communication technology has received wide attention. As one of the key technologies of 6G, terahertz (THz) communication technology has the characteristics of ultra-high bandwidth, high security and low environmental noise. In this paper, a THz duplexer with a half-wavelength coupling structure and a sub-harmonic mixer operating at 216 GHz and 204 GHz are designed and measured. Based on these key devices, a 220 GHz frequency-division multiplexing communication system is proposed, with a real-time data rate of 10.4 Gbit/s for one channel and a transmission distance of 15 m. The measured constellation diagram of two receivers is clearly visible, the signal-to-noise ratio (SNR) is higher than 22 dB, and the bit error ratio (BER) is less than 10^{-8}. Furthermore, the high definition (HD) 4K video can also be transmitted in real time without stutter.

Keywords: frequency-division multiplexing; sub-harmonic mixer; terahertz communication; terahertz duplexer

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1 Introduction

With the development of wireless communication technology, the global mobile data traffic is growing exponentially, and the demand for high-speed and low-latency data transmission is gradually growing[1]. However, the currently used millimeter wave band cannot achieve these visions, so researchers turn their attention to the terahertz (THz) band. THz waves range from 0.1 to 100 THz, and the THz wireless communication has strong directionality, excellent security, and wide bandwidth, which has a communication rate of more than 100 Gbit/s.

The NTT Laboratories in Japan first started research on THz wireless communication in 2004, the carrier frequency of which is 120 GHz under amplitude shift keying (ASK) modulation for a data rate of 10 Gbit/s[2]. In recent years, this team has developed 300 GHz power amplifiers, low-noise amplifiers, and base-wave mixers based on 80 nm InP-HEMT technology in Ref. [3], and the proposed THz wireless link has achieved a wireless data rate of up to 120 Gbit/s based on 16 quadrature amplitude modulation (QAM) modulation over a transmission distance of 9.8 m. In Ref. [4], the communication system is developed by Karlsruhe Institute of Technology with a carrier frequency of 237.5 GHz under 16QAM modulation. The proposed system achieved 100 Gbit/s over a distance of 20 m. With the support of the DOTSEVEN project, the team of the Institute for High Frequency and Communication Technology has developed a 240 GHz full integrated transceiver chip based on a 130 nm SiGe Bi-COMS technology to achieve 10 Gbit/s over a transmission distance of 15 cm and a BER of less than 10^{-9}[5]. Recently, this team has also achieved Quadrature Phase Shift Keying (QPSK) modulated signal transmission at a transmission distance of 1 m and a transmission rate of 110 Gbit/s with a measured error vector magnitude (EVM) of 31.9% based on the 130 nm SiGe heterojunction bipolar transistor (HBT) technology in the 220–225 GHz band[6]. The 220 GHz communication system[7] built by University of Electronic Science and Technology of China is based on the THz solid-state receiving front-end, which can realize 3.52 Gbit/s wireless communication over a distance of 200 m using QPSK modulation. In Ref. [8], the Chinese Academy of Engineering Physics developed a 140 GHz wireless link for offshore communication, which has

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a transmit power of 33 dBm and finally achieved a transmission distance of 27 km with 500 Mbit/s. According to these works, the solid-state THz communication technology has fully demonstrated its great application potential and research value in high-rate wireless communication. However, the exploration of THz communication is still limited to point-to-point communication. Therefore, the research on the THz frequency-division multiplexing wireless link is very important to THz communication.

In this paper, we propose a 220 GHz frequency-division multiplexing communication system, which adopts the classical super outlier architecture, focusing on the design including a 220 GHz sub-harmonic mixer, duplexer and THz frequency-division multiplexing communication system, which finally realizes the transmission data rate of 10 Gbit/s for up/down link over a distance of 15 m.

2 System Architecture

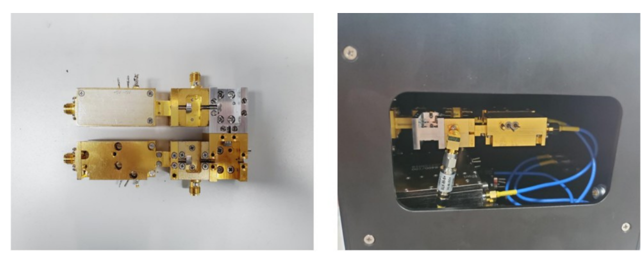
Full duplex communication systems often use a time division multiplexing (TDM) mode, a frequency-division multiplexing (FDM) mode and an isolation mode based on waveguide-guided orthogonal couplers[10]. During these modes, FDM is to divide the total bandwidth used for the transmission channel into two sub-carriers with different frequencies for receiving and transmitting. Although the two channels occupy different frequencies and large spectrum resources, the THz band has huge spectrum resources. Therefore, the FDM mode is extremely suitable for realizing THz full duplex communication.

In this paper, a 220 GHz full-duplex wireless communication system is built in a frequency-division multiplexing mode, and the system block diagram is shown in Fig. 1. The baseband signal is upconverted by a C-band frequency conversion module, which is filtered out of the upper sideband and fed into a THz mixer to upconvert to the THz band, and then filtered by a THz duplexer to remove the mirror frequency and get the radio frequency (RF) signal. The operating frequency of the uplink channel is 197.3 – 199.9 GHz, and that of the downlink channel is 207 – 213 GHz. The RF link of the communication system is shown in Fig. 2. To effectively reduce the space occupied by the link, the RF link is connected to the duplexer with a curved waveguide.

3 Critical Components of System

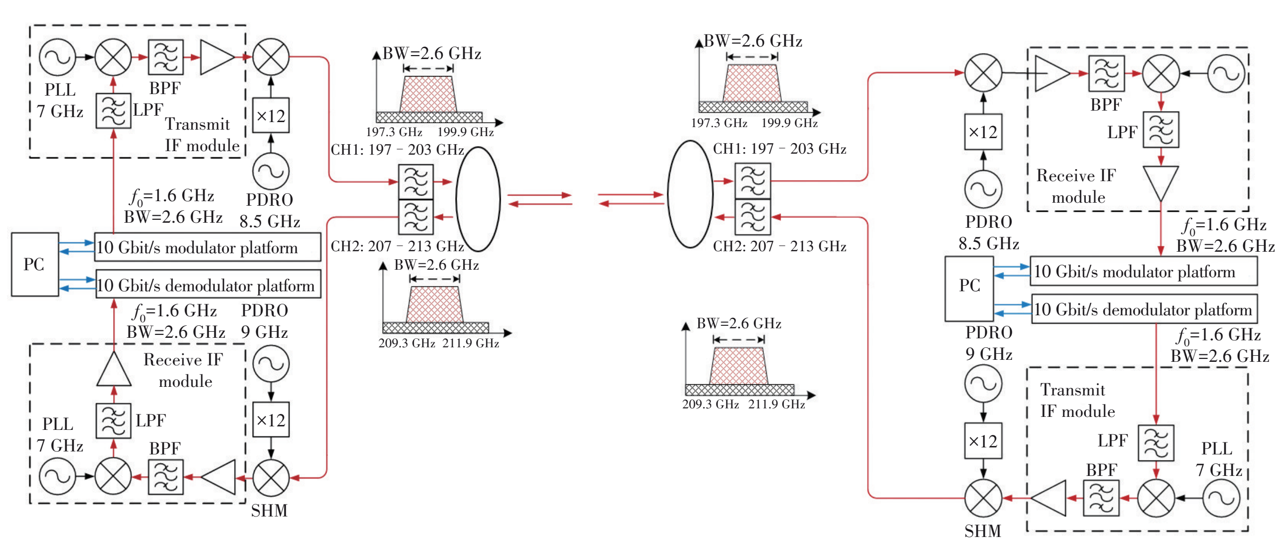
3.1 220 GHz Sub-Harmonic Mixer Study

A mixer is a crucial device of a THz communication system that uses a nonlinear device of solid-state devices to generate an output signal containing multiple frequency components[9]. The mixer consists of an RF input structure, a local oscillator (LO) input structure, multiple filters, inverted parallel diode



(a) RF link (b) Chassis diagram

▲Figure 2. Front-end link of the communication system



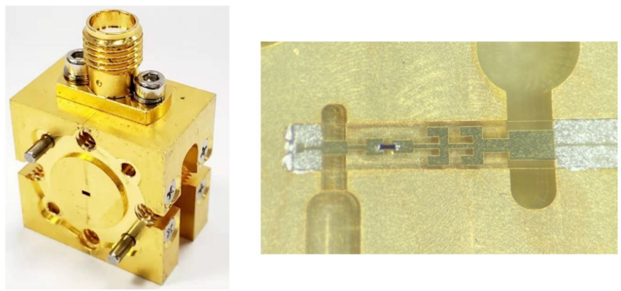
(a) Upstream transmit and downstream receive (b) Downstream transmit and upstream receive

BPF: bandpass filter
BW: bandwidth
IF: intermediate frequency
LPF: low pass filter
PDRO: phase-locked dielectric resonator oscillator
PLL: phase-locked loop
SHM: sub-harmonic mixer

▲Figure 1. Communication system block diagram pairs, and a matching network. In this paper, we design a 220 GHz sub-harmonic mixer using Schottky diodes, and the circuit substrate is based on a 50 μm quartz substrate.

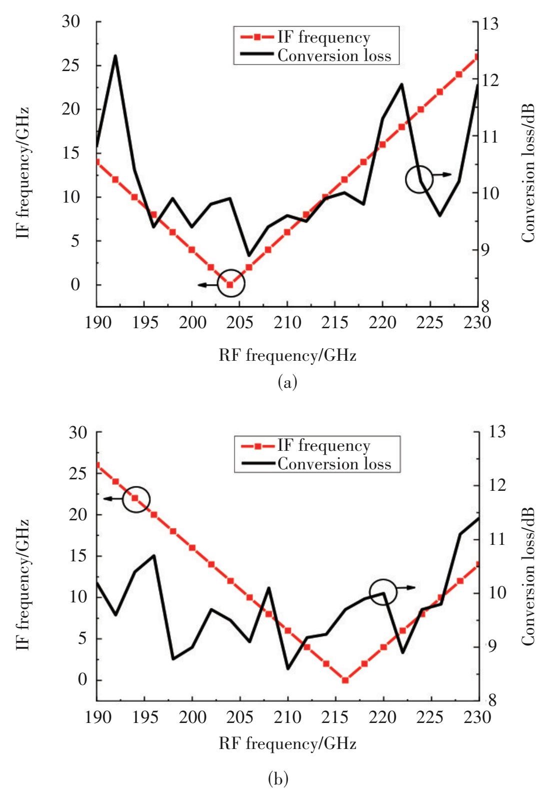
The mixer and the internal circuit are shown in Fig. 3. The cavity is made of brass, which is gold-plated on the surface. During the test, the output power of the LO link is controlled within 3 – 8 mW, and the input RF signal power is uniformly adjusted to −10 dBm.

The measured result shows that when the LO and RF signal input 204 GHz and 195 – 220 GHz, respectively, the frequency conversion loss is less than 10 dB, which is 8.8 dB at minimum, as shown in Fig. 4(a). After changing the LO frequency to 216 GHz, the frequency conversion loss is less than 10.3 dB, which is 8.9 dB at minimum, as shown in Fig. 4(b).



(a) Overall appearance (b) Internal circuit

▲**Figure 3. 220 GHz sub-harmonic mixer**

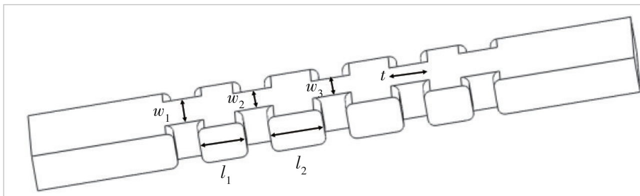


▲**Figure 4. Frequency conversion loss test results of mixers with different LO frequencies: (a) 204 GHz and (b) 216 GHz**

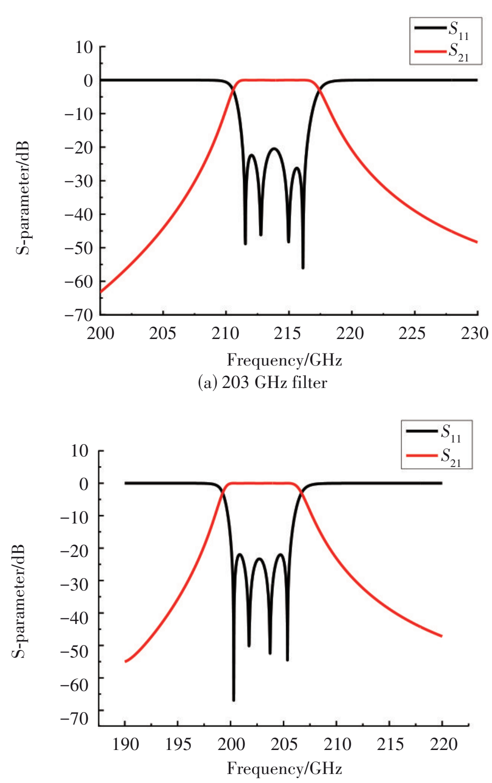
3.2 220 GHz Duplexer Study

In this paper, the designed duplexer adopts the reactance-coupled bandpass filter structure, as shown in Fig. 5. The mode of each resonant cavity is TE_{101} and the resonant cavity length is approximated as a half wavelength. The parameters affecting the filter performance are mainly the length of each resonant cavity l_i and the width of each coupling window w_i. Changing l_i has a significant effect on the center frequency, and the length of the resonant cavity near the center l_2 has a higher effect on the center frequency than l_1. Adjusting w_i has a certain effect on the in-band characteristics and bandwidth.

Two different band filters with center frequencies of 203 GHz and 214 GHz are designed. It can be seen from Fig. 6 that the simulation results show the bandwidths are 6 GHz and the in-band insertion loss (IL) is lower than 0.1 dB.



▲**Figure 5. Filter structure diagram**

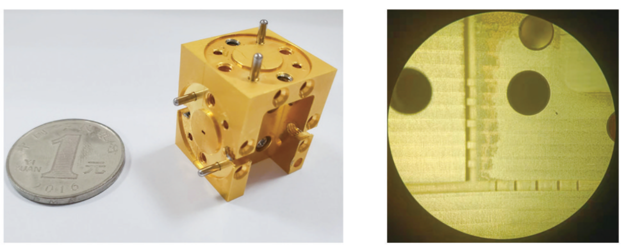


(a) 203 GHz filter

(b) 213 GHz filter

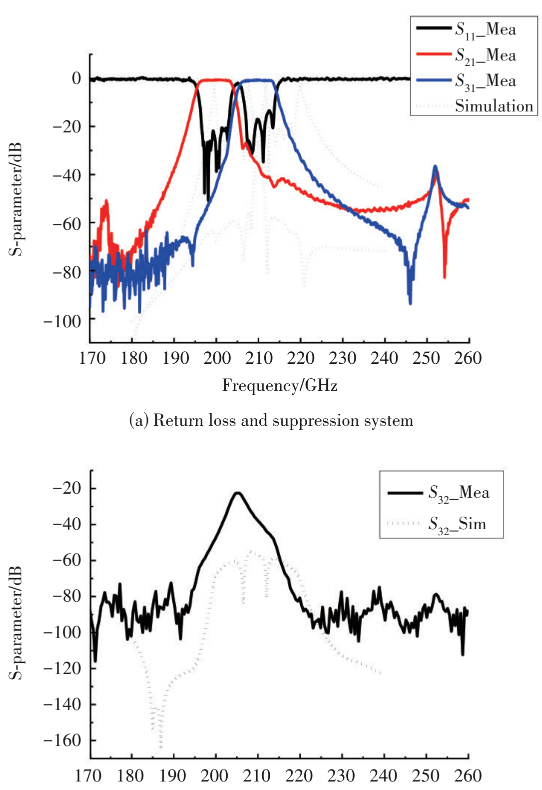
▲**Figure 6. Filter simulation results**

After filters are designed, every individual filter is directly connected through T-junctions[11] to form a multiplexer. The machining physical drawing and microscope photo of the internal structure are shown in Fig. 7. The proposed duplexer is fabricated by computerized numerical control (CNC) milling technology. The cavity is made of brass with a gold-plated surface. The simulation and measured results show that the duplexer passband is 197 – 203 GHz and 207 – 213 GHz, the isolation degree is 22.51 dB at 205 GHz, the average in-band return loss is less than 15 dB, and the average in-band insertion loss (IL) is less than 0.8 dB, which is 0.58 dB at minimum, as shown in Fig. 8. Compared with the simulation results, the overall frequency shift is 3 GHz and the isolation degree is 8 dB worse. However, the single-channel bandwidth is not different from the simulation results. The reason may be that the length of the resonant cavity in the center of the two channels is larger than the simulated value, and the width of the coupling window is similar to the simulated value, which leads to the same bandwidth and downward frequency shift.



(a) (b)

▲ **Figure 7. Physical diagram of duplexer: (a) appearance and (b) microscope photo of internal structure**



(a) Return loss and suppression system

(b) Isolation between Ports 2 and 3

▲ **Figure 8. Duplexer simulation and test data**

4 Measurement Results

For terahertz wireless communication, the link-budget of the system mainly includes transmit power, antenna gain, free space loss, and atmospheric attenuation[12]. The received power can be calculated as follows:

$$P_R = P_T + G_T + G_R + 20\lg\left(\frac{c}{4\pi R_f}\right) - L_0 - L_{ex}, \tag{1}$$

where P_T is the transmitter output power in dBm, G_T and G_R are antennas gains, R is the transmission distance, L_0 is atmospheric attenuation which is less than 0.01 dB, and L_{ex} is an excess loss set to 3 dB.

The transmitting antenna and receiving antenna both use the WR-4 band lens antenna. The baseband power input to the 220 GHz sub-harmonic mixer is less than −10 dBm, and combined with the test results in Section 3, we can get the antenna transmit power P_T less than −20 dBm. Therefore, the maximum received power of the receiver is −35.78 dBm.

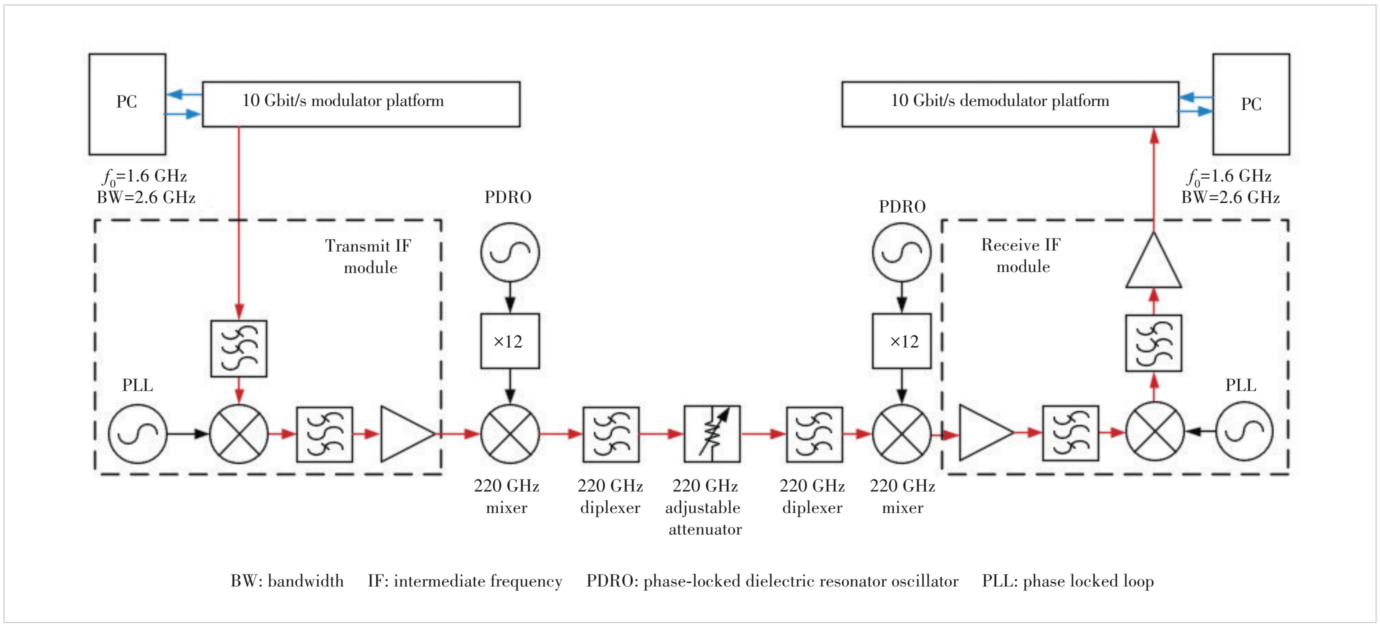
Receiver sensitivity $S_{i,\min}$, which is the minimum received power of the receiver and can be calculated as follows:

$$S_{i,\min} = -174 + 10\lg B + \mathrm{NF} + \mathrm{SNR}, \tag{2}$$

where B is signal bandwidth as 2.6 GHz, NF is the receiver noise factor that can be calculated from the system cascade noise factor calculation formula as 13 dB, and SNR is the minimum signal-to-noise ratio required for baseband demodulation which requires at least 19 dB using 16QAM modulation. Therefore, the receiver sensitivity can be calculated as −46.02 dBm. The difference between the received power and the receiver sensitivity is 10.24 dB, which means the system has a link-budget of 10.24 dB.

The block diagram of the single-channel experiment is shown in Fig. 9. The LO signals of the transmitter and receiver are both provided by the 110 GHz twelve-octave frequency multiplier. The influence of phase white noise at the far end of the local oscillator on the communication quality is great[13], and the deterioration of phase white noise at the far end of the local oscillator with the frequency multiplier is 20 $\log_{10}(n)$, so the input of the local oscillator signal should reduce its far-end white noise as much as possible. Compared with a phase-locked loop (PLL), the phase-locked dielectric resonator oscillator (PDRO) has a better phase noise. Therefore, the input of this oscillator selects PDRO at 8.5 GHz and 9 GHz, and its phase noise at 1 MHz can reach −131 dBc/Hz.

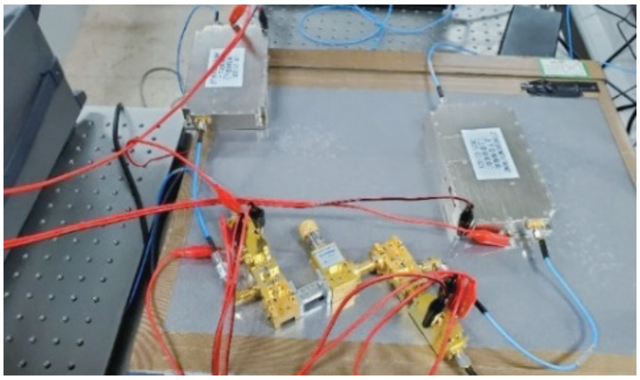
The experimental scenario is shown in Fig. 10. In the trans-



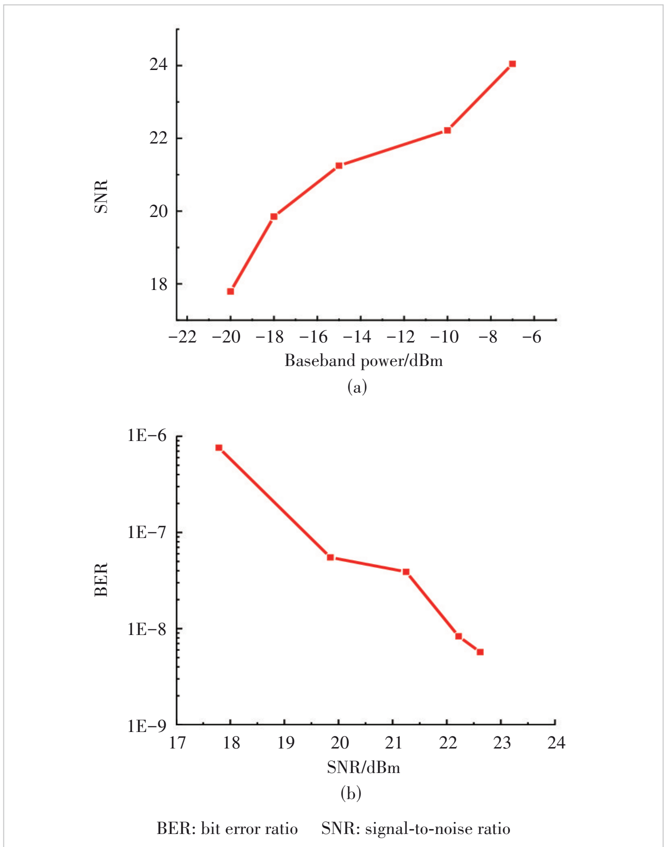
▲Figure 9. Single-channel experimental block diagram

mit link, the baseband signal is first upconverted by the C-band frequency conversion module, filtered out of the upper sideband and then fed into the THz mixer to be upconverted to the THz band, and then filtered out of the mirror frequency by the THz duplexer. In the receive link, the RF signal enters the THz mixer after the duplexer and is down-converted to the intermediate frequency (IF) signal. It is then down-converted to the baseband signal by the C-band frequency conversion module and demodulated after amplification and filtering. The transmit and receive links are connected with a THz adjustable attenuator for simulating the propagation loss of THz signals in free space. The relationship between different baseband power and the SNR is demonstrated in Fig. 11(a), which shows that there is no significant change in the demodulation SNR with the baseband power above −15 dBm and when the baseband power is below −20 dBm, the SNR deteriorates further. Fig. 11(b) shows the relationship between the demodulation SNR and BER.

The constellation diagrams corresponding to different SNRs

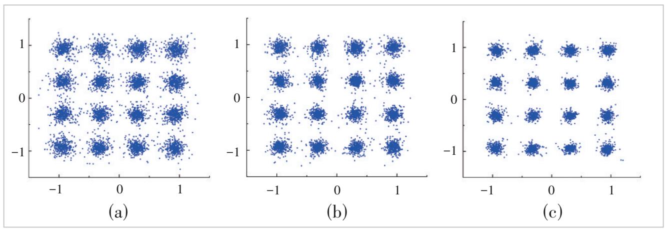


▲Figure 10. Single-channel experimental scene diagram



▲Figure 11. Single-channel test data: (a) relationship between transmit power and SNR and (b) relationship between SNR and BER

are demonstrated in Fig. 12, which shows that the communication results are basically the same when the LO frequency is 204 GHz and 216 GHz. Keeping the above test platform unchanged, the baseband modulation mode is changed to

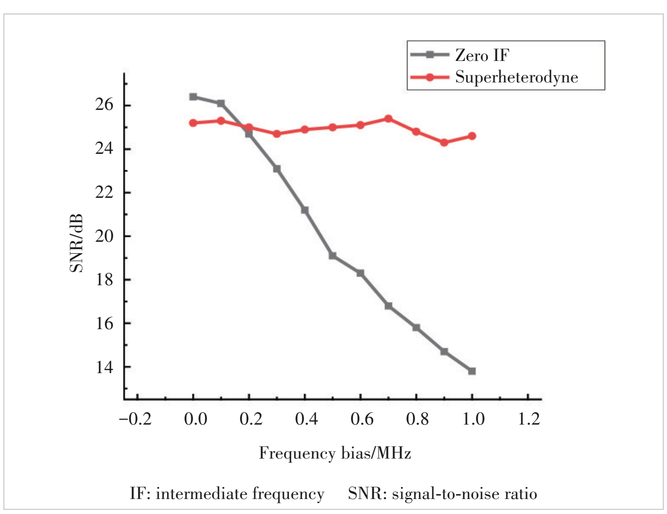


▲ **Figure 12. Constellation diagrams with different signal-to-noise ratio SNR: (a) 17.79 dB, (b) 19.85 dB, and (c) 22.62 dB**

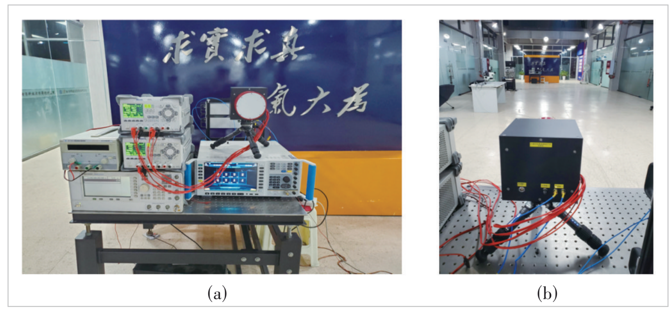
64QAM and the attenuator is adjusted to make the best performance. Then the performance at the LO frequency of 204 GHz and 216 GHz are tested respectively.

The THz attenuation is removed so that the transmitter and the receiver are directly connected back-to-back. The PDRO at the receiver side is replaced as the signal source is input to achieve the effect of transmitting and receiving LO frequency offset by changing the signal source input. The range of frequency offset measurement is 0 – 1 MHz with a step of 0.1 MHz. The variation of SNR with the amount of frequency offset is shown in Fig. 13. The baseband signal in the receiving section is a single sideband. The LO frequency bias corresponds to the overall offset of the baseband spectrum and there is no signal crossover. Therefore, as long as the frequency bias is less than the threshold, the SNR is basically unchanged. When the frequency offset exceeds the threshold value, the SNR deteriorates sharply and the BER is 1.

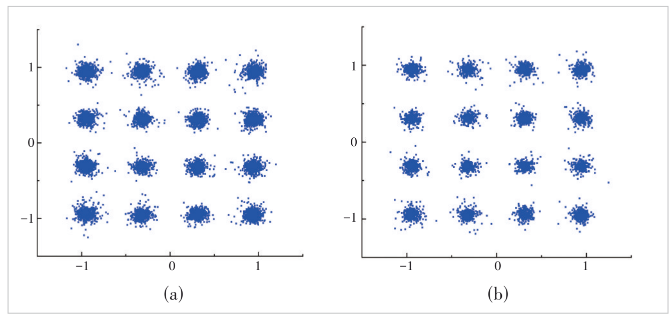
After measurement, the frequency bias threshold of this communication system is 2.5 MHz. The photograph of the communication experiment is shown in Fig. 14. The corresponding constellation diagram is shown in Fig. 15, where the demodulation SNR of the uplink channel is 22.91 dB when the LO frequency is 204 GHz and the demodulation SNR of the downlink channel is 23.19 dB when it is 216 GHz. The BER is less than 10^{-8}. The final transmission distance of this communication system is 15 m, which can reach 20 m by calculation because of spare capacity in the link. The comparison of the previously published THz wireless links with ours is shown in Table 1.



▲ **Figure 13. Variation of SNR with different frequency bias**



▲ **Figure 14. (a) Uplink transmit and downlink receive; (b) downlink transmit and uplink receive**



▲ **Figure 15. Constellation diagram: (a) 204 GHz uplink; (b) 216 GHz downlink**

5 Conclusions

In this paper, the front-end key components including a 220 GHz sub-harmonic mixer and a 220 GHz duplexer are designed for the application requirements of the THz frequency-division multiplexing communication system. The sub-harmonic mixer is designed based on the domestic Schottky diode, which has a fixed fundamental frequency of 204 GHz and 216 GHz. The frequency conversion loss is less than 10.5 dB at 20 GHz. The 220 GHz duplexer is designed based on the principle of the cavity filter. The range of the duplexer passband is 197 – 203 GHz and 207 – 213 GHz, and the return loss in the common port is less than 15 dB, which can effectively divide the channel of the communication system and suppress the mirror frequency. Based on the above circuit de-

▼ **Table 1. Experimental prototype performance comparison of terahertz (THz) wireless communication systems**

Reference	Frequency/GHz	Transmission Rate/(Gbit/s)	Modulation Format	Transmission Distance/m	Real-Time Transmission
Ref. [2]	120	10	ASK	1	No
Ref. [3]	290	120	16QAM	9.8	No
Ref. [5]	220 – 225	110	QPSK	1	No
Our proposed work	**220**	**10.4**	**16QAM**	**15**	**Yes**
	204/216	**10.4/10.4**	**16QAM**	**15**	

ASK: amplitude shift keying QPSK: Quadrature Phase Shift Keying
QAM: quadrature amplitude modulation

sign, the 220 GHz frequency-division full duplexer communication system is proposed, which realizes real-time high-speed communication with a transmission distance greater than 15 m, and uplink and downlink transmission rates of 10.4 Gbit/s, respectively. The measured BER is lower than 10^{-7}. Furthermore, the HD 4K video can be transmitted in real time. This work realizes a high-rate and long-range THz communication system that has broad application prospects in wireless communication. This paper builds a 220 GHz frequency-division multiplexing communication system, which adopts non-coherent demodulation to achieve a transmission distance of 15 m, an uplink and downlink transmission rate of 10.4 Gbit/s each, and a BER lower than 10^{-7}.

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Biographies

ZHANG Bo (bozhang@uestc.edu.cn) received his BE, MS, and PhD degrees in electromagnetic field and microwave technology from the University of Electronic Science and Technology of China (UESTC) in 2004, 2007, and 2011, respectively. He has been a senior member of IEEE in 2015. He is currently a professor with School of Electronic Science and Engineering, UESTC and Yangtze Delta Region Institute (Huzhou), UESTC. His research interests are terahertz solid state technology and system.

WANG Yihui received her BE degree in electronic engineering from University of Electronic Science and Technology of China (UESTC) in 2017, and is currently working toward her MS degree in terahertz solid-state circuit technology in UESTC, focusing on microwave, terahertz solid-state circuits, and terahertz communication.

FENG Yinian received his BS degree in electronic engineering from University of Electronic Science and Technology of China (UESTC) in 2016, where he is currently pursuing his PhD degree in terahertz solid-state circuit technology. His research interests include microwave, terahertz solid-state circuits, and terahertz communication.

YANG Yonghui received his BS degree in information countermeasure techniques and MS degree in electronic information engineering from Xidian University, China in 2006 and 2010, respectively. Since 2010, he has been with ZTE Corporation, where he focuses on wireless communications. His current research interests include 5G and 6G technology, millimeter-wave and terahertz communication.

PENG Lin received his BS degree in information engineering and MS degree in electromagnetic field and microwave techniques from Nanjing University of Science and Technology, China in 2004 and 2006, respectively. Since 2006, he has been with ZTE Corporation, where he focuses on the research of wireless communications. His current research interests include beyond-5G and 6G technology, millimeter-wave and terahertz communications and intelligent reflecting surface for wireless applications.