220 GHz outdoor wireless communication system based on a Schottky-diode transceiver

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Abstract: In this paper, an all-electronic outdoor wireless communication system based on a Schottky-diode transceiver at 220 GHz is reported. The transceiver is implemented by the use of in-house designed 220 GHz low-noise Schottky diode-based subharmonic mixers (SHMs), which simplifies the system setup and demonstrates the feasibility of Schottky technology for terahertz (THz) communication. The system setup, performance of critical components and link budget calculation are presented. The wireless link quality is evaluated in terms of the error vector magnitude (EVM). 3.52 Gbit/s real-time three-dimension (3D) glass-free video transmission is achieved over an outdoor distance of 200 m by the use of quadrature phase shift keying (QPSK) modulation.

Keywords: terahertz, wireless communication, Schottky-diode subharmonic mixer, quadrature phase shift keying (QPSK), 220 GHz

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

[1] S. Cherry: IEEE Spectr. \textbf{41} (2004) 58. DOI:10.1109/MSPEC.2004.1309810
[2] H. J. Song and T. Nagatsuma: IEEE Trans. THz Sci. Technol. \textbf{1} (2011) 256. DOI:10.1109/TTHZ.2011.2159552
[3] A. Hirata: IEICE Electron. Express \textbf{12} (2015) 20152003. DOI:10.1587/elex.12.20152003
[4] S. Koenig, D. Lopez-Diaz, J. Antes, F. Boes, R. Henneberger, A. Leuther, A. Tessmann, R. Schmogrow, D. Hillerkuss, R. Palmer, T. Zwick, C. Koos, W. Freude, O. Ambacher, J. Leuthold and I. Kallfass: Nat. Photonics \textbf{7} (2013) 977. DOI:10.1038/nphoton.2013.275
[5] T. Nagatsuma, S. Horiguchi, Y. Minamikata, Y. Yoshimizu, S. Hisatake, S. Kuwano, N. Yoshimoto, J. Terada and H. Takahashi: Opt. Express \textbf{21} (2013)
As the demand for wireless data consumption grows exponentially [1], it is a natural option to exploit the terahertz (THz) frequency band for the abundance of absolute bandwidth [2, 3]. Over the past few years, THz wireless communication using electro-photonic technologies has seen impressive progress [4, 5], but to adopt this approach will increase the system size because of the requirement for
extra optical components. Recently, utilizing all-electronic technologies to fulfill THz wireless transmission attracts significant attention owing to the potential of system-on-chip integration [6, 7, 8, 9, 10, 11]. In this regard, the existing primary technological bottleneck is the lack of enabling high-performance and cost-effective electronic devices. Compound semiconductor transistor-based electronic devices can provide signal amplification that may improve the transmitting power and receiver’s sensitivity. However, at the current stage, the complexity of the fabrication process makes these devices in the THz band extremely costly. Thus, to investigate an alternative enabling technology of lower cost and easier technological access will add immense benefit to the THz community.

Schottky-technology electronic devices have a long history applied in the radio astronomy and earth observation areas due to the high sensitivity and relatively simpler device fabrication process compared with the transistor counterpart in the THz band [12]. These devices now even feature commercial availability for THz applications [13]. This provides an effective gateway to realize THz wireless communication. Besides, Schottky-device-based circuits can also adopt the system-on-chip concept [14]. Therefore, to investigate the feasibility of THz wireless transmission based on Schottky technology is of both academic and technological significance. In recent years, a few publications have demonstrated THz wireless data links using this technology [15, 16, 17]. However, these works were carried out in limited lab environment. Future practical THz communication requires better environment flexibility and larger transmission distance.

In this paper, we propose a wireless communication system based on a Schottky-diode transceiver working at the atmospheric window frequency of 220 GHz. A 220 GHz subharmonic mixer (SHM) utilizing Schottky diodes is designed and measured yielding low-noise performance, which brings simplicity for the system implementation. The wireless link quality is addressed using error vector magnitude (EVM) measurements and the system achieves 3.52 Gbit/s real-time transmission of three-dimensional (3D) glass-free video programme using quadrature phase shift keying (QPSK) modulation over an outdoor 200 m distance.

2 Schottky diode subharmonic mixer at 220 GHz

The SHM is the key component in the system as its noise performance makes vital influence on the system’s sensitivity (Detailed system setup is presented in Section 3.). An anti-parallel Schottky diode pair is selected as the nonlinear element of the SHM in this work. The diodes are AP1 series from the Rutherford Appleton Laboratory (RAL) [18, 19]. The diode topologies are formed on a 15 μm thick GaAs semi-insulating substrate as shown in Fig. 1. The active diode structures consist of a n-GaAs layer (doping density: $2 \times 10^{17}$ cm$^{-3}$) and a highly doped n$+$-GaAs layer (doping density: $5 \times 10^{18}$ cm$^{-3}$). Lithography, metal deposition, and etching processes are used for the formation of diode key features including the Schottky contacts, the anodes, the airbridge fingers and the ohmic contacts [18, 19]. The airbridge fingers suspended over the surface channel bring the benefit of parasitic capacitance reduction.
With the diode electrical parameters inclusive of the zero voltage junction capacitance $C_{j0} = 1.4 \text{ fF}$, saturation current $I_S = 2.5 \text{ fA}$, series resistance $R_S = 12 \Omega$ and ideality factor $n = 1.17$, the embedding impedances to yield optimum noise performance can be determined. The embedding network consists of quartz-based microstrip line circuits and E-plane split-block waveguide structures. The 75 $\mu$m thick quartz is suspended on the lower part of the housing metallic waveguide block as shown in Fig. 2. The Schottky diode pair is flip-chip soldered across the gap between the gold lines processed on the quartz. The RF signal comes through a WR-4 rectangular waveguide and is coupled to the diodes via a grounded probe. An RF and dc ground is provided by contacting the end of the gold track to the waveguide wall. The local oscillator (LO) filter prevents the RF signal from leaking through the WR-8 waveguide to the LO input port, but gives the LO power a low loss feeding path to the diodes. By the same token, the intermediate frequency (IF) signal is output through the IF filter without the LO leakage to the IF end. At this end, a K-type connector is used as the IF output port. The nonlinear behavior of the SHM is simulated using the harmonic balance module integrated in the Agilent’s Advanced Design System (ADS) software suite by taking into account the electromagnetic properties of the diode geometry, microstrip lines and waveguide structures calculated using the ANSYS’s HFSS software.

The SHM’s noise performance is characterized using the standard Y-factor measurement routine at RAL [20]. The test setup is shown in Fig. 3. A pyramidal blackbody at room temperature and cooled in the liquid nitrogen is used as the hot and cold load respectively. The IF output is amplified by the IF chain before power...
detected by the spectrum analyzer. The double side band (DSB) noise temperature and DSB conversion loss can therefore be extracted from the Y-factor measurements [20], which are plotted in Fig. 4. The SHM’s DSB noise temperature and DSB conversion loss with the IF of 2 GHz are below 1000 K and 8 dB respectively from 208 GHz to 232 GHz. The LO pump power is 2–4 mW.

![Fig. 3. 220 GHz SHM noise performance test setup.](image)

![Fig. 4. Measured performance of the 220 GHz SHM.](image)

### 3 System setup

The system consists of transmitter (Tx) and receiver (Rx) units as shown in Fig. 5. QPSK modulation and demodulation take place in the frequency range centered at 10.8 GHz. 220 GHz Schottky-diode SHMs function as the frequency up- and down-converters in the heterodyne transceiver scheme. LO modules for both of the Tx and Rx are designed in the same frequency and power configuration. Each LO module contains two phase-locked loops (PLLs) taking the frequency reference from a 50 MHz crystal oscillator (CO). One of the two PLLs generates 10.8 GHz LO power (power level = 100 mW, phase noise < −90 dBc/Hz@10 kHz) to feed the in-phase/quadrature-phase (I/Q) modulator and demodulator in the Tx and Rx respectively. The other one provides 13 GHz frequency as the input to an 8-time frequency multiplier chain resulting in 104 GHz LO power to pump the SHM (power level = 3.5 mW, phase noise < −90 dBc/Hz@10 kHz). The QPSK modulation and demodulation in principle are implemented using commercially available X-band I/Q mixers. The balanced-to-unbalanced (balun) transformers are em-
ployed to realize the differential configuration for the I/Q baseband signal transmission, which provides the merit to eliminate potential interference from the environment.

For the current system application, the LO frequency for SHMs is set to be 104 GHz and the IF is centered at 10.8 GHz. In this case, to measure the SHM’s single side band (SSB) conversion loss, a 218.8 GHz source with the output power calibrated at $-20$ dBm is used to provide the RF test signal. By pumping the SHM at 104 GHz and knowing the 10.8 GHz IF output power, its SSB conversion loss is measured to be 9.2 dB. The corresponding SSB noise temperature is estimated to be 2122 K when performing the link budget calculation displayed in Table I. The transmitting power to feed the Cassegrain antenna (gain = 52 dBi) is measured to be $-14.2$ dBm using an Erickson PM4 power meter. The calculated output signal to noise ratio at the Rx is 25.9 dB, which exceeds the threshold of QPSK demodulation criteria.

![Schematic diagram of the 220 GHz wireless communication system. (a) transmitter (b) receiver](image)
The existence of the two band-pass filters (BPFs) at the Tx and Rx ensures SSB operation, which rejects the lower sideband and results in the operational frequency band of 217.7~219.9 GHz (centered at 218.8 GHz) when the baseband signal is 3.52 Gbit/s (rolling factor = 0.25). The insertion loss in the passband of the BPFs is within 2 dB. At the Rx, the frequency down-converted signal is amplified by an automatic gain control (AGC) module, which yields maximum gain of 70 dB and dynamic range of 40 dB with a typical noise figure of 2 dB. The AGC module is designed to offset the possible variation of the received power level caused by the transmission distance, meteorological changes and wireless channel properties in the outdoor environment. Integrated with an amplitude equalizer, the AGC module provides sufficient power level within ±1 dB amplitude unbalance in the operational frequency range for the I/Q demodulator to detect.

### 4 Outdoor experimental demonstration

Before transmitting video programme, the wireless link quality was firstly evaluated in terms of the EVM [21]. The experiment was conducted over an outdoor 200 m distance under a clear sky condition. An Agilent M8190A arbitrary waveform generator (AWG) with a sample rate of 8 GSa/s was used to create I/Q baseband test data signals in the differential form to feed the 4-way input ports of the modulator at the Tx. At the Rx, the demodulated I/Q data signals were captured by an Agilent real-time 4-channel oscilloscope DSO91304A with a sample rate of 40 GSa/s. The carrier recovery was realized in the digital domain using Agilent’s vector signal analyzing (VSA) software and this software was also used to map constellation diagrams and analyze EVM values.

![Constellation diagrams and EVM measurements at different data rates](image)

**Fig. 6.** Constellation diagrams and EVM measurements at different data rates
Fig. 6 shows the constellation diagrams with the corresponding EVM values at different data rates. The EVM values grow as the data rate increases. The main reason of the distortion comes from the I/Q imbalance in the modulator and demodulator. According to [21], as for a QPSK scheme, the EVM value of 21% can be translated into an uncorrected bit error rate (BER) better than $10^{-5}$. This is completely sufficient for applying forward error correction (FEC) [22].

The clear constellation diagrams and good EVM values indicate that the transceiver’s performance is sufficient for video transmission in the outdoor environment. Therefore, the system was subsequently validated by transmitting real-time 3D glass-free video programme which consumes 3.52 Gbit/s data rate. The Tx and Rx were separated 200 m away from each other as well and were connected to the corresponding baseband units (shown in Fig. 7) in which the carrier recovery, channel equalization, data coding and decoding were performed. A customized 3D glass-free screen was used to present the video programme. Smooth and clear presentation was continuously achieved over a long-time period.

Table II summarizes the performance of this system and the recently published works using Schottky-diode transceivers. Through the development of a low-noise Schottky SHM and comprehensive consideration of the system setup, larger data rate and further transmission distance in the outdoor environment have been achieved in this work.

| Reference | Frequency (GHz) | Data rate (Gbit/s) | Distance (m) | Remarks |
|-----------|----------------|--------------------|--------------|---------|
| [15]      | 300            | 0.096              | 52           | indoor  |
| [16]      | 588            | < 1                | < 1          | indoor  |
| [17]      | 340            | 3                  | 50           | indoor  |
| this work | 220            | 3.52               | 200          | outdoor |
To the best of authors’ knowledge, the work presented in this paper is the first multi-Gbit/s outdoor wireless data transmission using a Schottky-diode transceiver at 220 GHz. When THz solid-state amplifiers become available, larger transmission distance can be expected. Furthermore, the I/Q scheme of the system makes it compatible with higher-order quadrature amplitude modulation (QAM) schemes, which are able to result in higher transmission data rate within the same bandwidth.

5 Conclusions

In this paper, a wireless communication system based on a Schottky-diode transceiver at 220 GHz is presented. A 220 GHz low-noise SHM utilizing Schottky diodes is developed for the transceiver. Outdoor 200 m real-time wireless transmission up to a data rate of 3.52 Gbit/s is achieved. The link quality is addressed in terms of EVM measurements and by transmitting 3.52 Gbit/s real-time 3D glass-free video programme. The transmission performance makes the system possible to be adopted as a prototype for practical point-to-point application scenarios. The result demonstrates the feasibility that Schottky devices can be applied for THz communication in the outdoor environment and shows the simplicity in terms of the system implementation by the use of low-noise Schottky SHMs. The merit brought by this work is to present a simpler and cost-effective technological approach to realize THz communication. In the future, with the development of solid-state electronics, Schottky devices combined with other cutting-edge electronic technologies will inspire new opportunities in the THz communication application and other emerging fields.

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