Terahertz Wireless Communications Using SiC-Substrate-Based Fermi-Level Managed Barrier Diode Receiver

Weijie Gao[#], Tsubasa Saijo[#], Keisuke Maekawa[#], Tadao Ishibashi[$], Hiroshi Ito[*], Tadao Nagatsuma[#]
[#]Osaka University, Japan
[$]Wavepackets LLC, Japan
[*]Kitasato University, Japan
gao.weijie.es@osaka-u.ac.jp

***Abstract*— Fermi-level managed barrier diode (FMBD) monolithically integrated on a silicon carbide (SiC) substrate has been experimentally demonstrated as an ideal terahertz detector with ultra-high sensitivity, low noise, and broad bandwidth. Employing such a FMBD as a receiver, 300-GHz band wireless communications with OOK and 16-QAM modulations are performed. For the OOK modulation, error-free transmission data rates of 32 Gbit/s and 25 Gbit/s are achieved for the direct and coherent (homodyne) detections, respectively. Limited by the imperfection of the optical light source, a below FEC-limit data rate of 48 Gbit/s is obtained for the 16-QAM modulation with the direct detection. Such a high-performance FMBD receiver promises the applications in beyond-5G communications.**

***Keywords*— terahertz, wireless communications, SiC substrate, Fermi-level managed, diode, direct detection, coherent detection.**

I. Introduction

Driven by the rapidly growing data traffic in wireless networks, recent research efforts have been dedicated to terahertz communications, which can provide large channel capacities to support not only mobile but backhaul connectivity [1]. Benefiting from both electronic and photonic technologies over the carrier frequency range from 300 to 500 GHz, a wireless transmission data rate over 100 Gbit/s has been reached. At the transmitter side, to generate stable, continuous, and high-quality terahertz signals, both electronic and photon-assisted strategies can be leveraged [1]. In particular, terahertz generation based on optical heterodyne method has been widely adopted due to its high efficiency and flexibility in precisely adjusting the frequency, phase, and bandwidth, while allowing for a large channel capacity [1]. Additionally, one key enabling component for terahertz generation is the photomixer, e.g., uni-traveling-carrier photodiode (UTC-PD), with high saturation power and broadband response [2].

Another important aspect of terahertz communications is the receiver. Commonly used terahertz detectors include Schottky barrier diodes (SBD) [3], field-effect transistors (FET) [4], and resonant tunnelling diodes (RTD) [5], while both direct (envelope) and coherent detections have been demonstrated on those detectors. With a much lower barrier height compared to that of the SBD, recently, Fermi-level managed barrier diodes (FMBD) have been proposed to achieve a higher-sensitivity, lower-noise, and broadband terahertz wave detection [6], [7], [8], [9], [10]. In [6], an InP/InGaAs FMBD grown on a semi-insulating InP substrate was proposed, where a bowtie antenna feeding the FMBD was implemented. To increase the output power of the intermediate frequency (IF) signals, a commercial transimpedance amplifier (TIA) was introduced. The assembled chip was packaged in a lens-mounted package, while an error-free transmission data rate up to 12.5 Gbit/s was achieved for the OOK modulated direct detection [8]. Such a relatively low data rate was mainly due to the limited bandwidth of the TIA and the relatively high coupling loss between the FMBD and the feeding structures. To improve the coupling efficiency, a modified sample was proposed in [7], where an individual quartz-substrate-based planar waveguide coupler connected to the FMBD chip was introduced, and the assembled structure together with a TIA was packaged in a rectangular hollow waveguide package [7], [9]. The enhanced coupling between the coupler and the rectangular waveguide enabled an appreciable power level of the received signal to be delivered to the FMBD, while the rectangular waveguide input provided an efficient interface to other components in the system. As a result, an improved error-free transmission data rate of 20 Gbit/s was achieved [9].

Most recently, a new InP/InGaAs FMBD together with on-chip coupler and low-pass filters monolithically integrated on a single silicon carbide (SiC) substrate has been proposed and experimentally verified to have a lower noise, higher sensitivity, and wider bandwidth compared to the previous versions [10]. In this work, comprehensive experiments are conducted on this SiC-substrate-based FMBD to demonstrate its superior performance in terahertz wireless communications.

II. Characteristics of FMBD

A. FMBD configuration

As shown in Fig. 1(a), the proposed FMBD consisting of n-InGaAs/InP/n-InGaAs layers with a junction area of around 0.5 μm^2 and a barrier height of 90 meV is fabricated on a 4H-SiC substrate through the epi-layer transfer techniques. In addition, a microstrip-line-based planar waveguide coupler and two stepped-impedance low-pass filters are introduced on the same substrate, so that the input RF waves can be efficiently coupled from the feeding hollow waveguide to the FMBD,

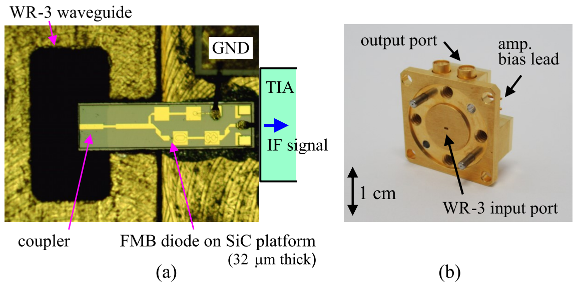

Fig. 1. Configuration of the SiC-substrate-based FMBD module. (a) Micrograph of the fabricated FMBD chip coupled to the WR-3 hollow waveguide. (b) Photo of the fabricated FMBD housed in a WR-3 waveguide package with a size of $20 \times 20 \times 8$ mm^3. The pictures are adopted from [10].

while the IF signals down-converted by the FMBD can be extracted with good RF isolations. The rectified/demodulated signals are then input into a commercial transimpedance amplifier (Semtech, GN1800) to increase the output power gain. Compared to other conventional substrate materials, the silicon carbide has a lower loss and a higher thermal conductivity able to significantly suppress the noise, while its high relative permittivity is suitable for realizing a miniatured integrated circuit operating at high terahertz frequencies [10]. In addition, the large Young's module of SiC material allows for fabrications with a very thin substrate thickness while maintaining a good device mechanical stability [10]. As shown in Fig. 1(b), the realized FMBD chip together with the TIA chip is housed in a WR-3 hollow waveguide package operating over the frequency range from 220-330 GHz. The FMBD is zero-biased in operation, while a +3.3 V is applied to the internal TIA through bias leads, and the TIA's differential output ports are connected to the SMPM connectors. Such a design leads to superior performance as a terahertz detector with a voltage sensitivity varying from 17 $\mathrm{kV\ W^{-1}}$ to 43 $\mathrm{kV\ W^{-1}}$ over 220–330 GHz and low noise equivalent power of 3×10^{-19} $\mathrm{W\ Hz^{-1}}$ at around 300 GHz with an LO power of only 30 μW for fundamental mixing [10].

B. Bandwidth

To characterize the bandwidth of the FMBD module, measurements are conducted with the experiment setup shown in Fig. 2. At the transmitter side, two free-running near-infrared laser sources with tunable wavelengths are adopted to generate optical beat signals, which are modulated by an electro-optic amplitude modulator (EOAM) with the baseband signal generated from a RF synthesizer. Amplified by an erbium-doped fibre amplifier (EDFA), the modulated optical signals are downconverted by a UTC-PD to the terahertz signal with a frequency equal to the frequency difference between two lasers. The FMBD module is then directly connected to the UTC-PD through a WR-3 rectangular waveguide, while its output signal is measured by a RF spectrum analyzer.

To measure the RF bandwidth of the FMBD, the baseband frequency is fixed as 1 GHz with an output power of 0 dBm, and the RF frequency is varied from 250 to 350 GHz with an interval of 4 GHz, where the output power from the UTC-PD

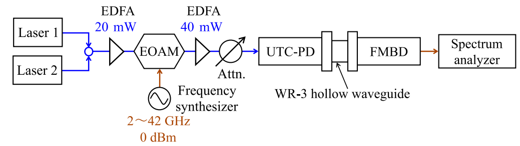

Fig. 2. Block diagram of the experimental setup for the FMBD bandwidth characterization. The wavelengths for lasers 1 and 2 are tunable. EDFA: Erbium-doped fibre amplifier, Attn.: attenuator, EOAM: Electro-optic amplitude modulator, UTC-PD: Uni-traveling carrier photodiode.

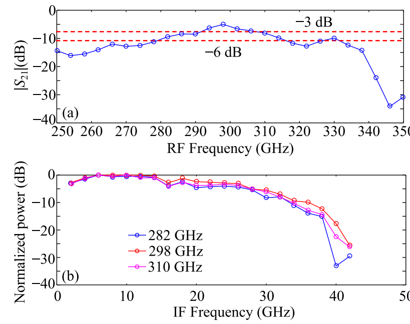

Fig. 3. Bandwidth of the FMBD module. Measured (a) RF bandwidth, and (b) IF bandwidth of the FMBD module. The output power of the UTC-PD is kept as −20 dBm (10 μW) for the RF bandwidth measurement. The output power of the FMBD for the IF bandwidth measurement is normalized.

is kept as constant as −20 dBm (10 μW), which is below the saturation level. As shown in Fig. 3(a), the measured transmission coefficient of the FMBD varies with a 3-dB bandwidth over 290-310 GHz, and a 6-dB bandwidth over 278-318 GHz. To characterize the IF response of the FMBD, three RF frequencies around 300 GHz are selected, while the baseband frequency driving the EOAM is varied from 2-42 GHz, where the EOAM frequency response is excluded. As indicated in Fig. 3(b), the measured normalized 3-dB bandwidth is around 26 GHz much narrower than the TIA bandwidth around 36 GHz, and it can be further improved by optimizing the design of the circuit on SiC substrate.

III. Communications Experiment

A. Direct detection

To verify the performance of FMBD in 300-GHz band communications, wireless transmission experiment with on-off keying (OOK) modulation and direct (envelope) detection is performed. The system setup is shown in Fig. 4, where the EOAM is driven by a pulse-pattern generator (PPG) with a maximum frequency of 32 GHz, while a bit error rate tester (BERT) together with an oscilloscope is adopted to measure the bit error rate (BER) and eye diagrams. The distance between the transmitting and receiving horn antennas is set as 1 cm, which can be further increased by adopting higher-gain antennas and/or adding dielectric lenses or parabolic mirrors. The carrier frequency in this measurement is selected as 298 GHz, where the FMBD shows a slightly higher sensitivity as compared in Fig. 3(b). The BER as a function of transmitter (UTC-PD) power at various data rates are measured as shown in Fig. 5(a), where an error-free transmission is achieved at a maximum data rate of 32 Gbit/s,

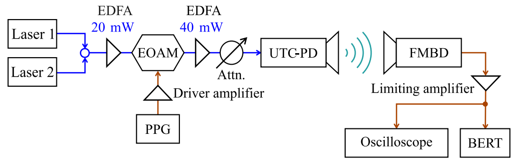

Fig. 4. Block diagram of the experimental setup for wireless communications with direct (envelope) detection. PPG: Pulse-pattern generator, BERT: bit-error-rate tester.

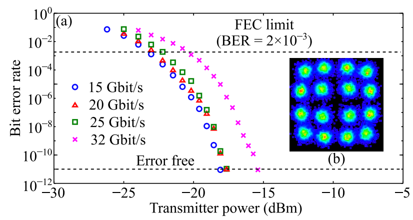

Fig. 5. Measured results for the direct detection. (a) Bit error rate versus transmitter power at various data rates with OOK modulation. (b) Constellation diagram for 16-QAM modulation at the baud rate of 12 Gbaud (48 Gbit/s) with EVM of 11.9%.

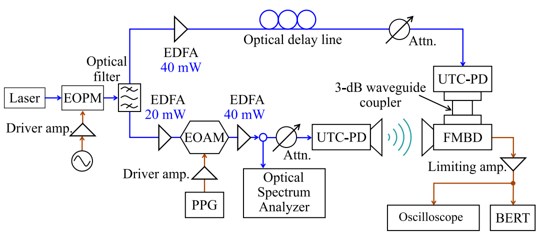

Fig. 6. Block diagram of the system setup for the FMBD coherent (homodyne) detection. EOPM: Electro-optic phase modulator.

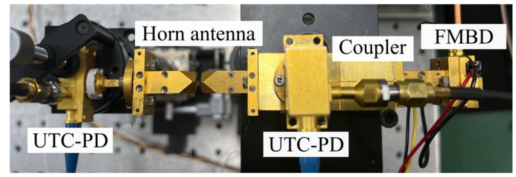

Fig. 7. Photo of measurement setup for the coherent detection with a close-up view of the transmitter and receiver.

which is much higher than that obtained with the quasi-optic FMBD (12.5 Gbit/s) [8] and the InP-substrate-based assembled FMBD module (20 Gbit/s) [9]. It is noteworthy that the UTC-PD power is almost identical for the data rates from 15-25 Gbit/s to achieve an error-free transmission, which further demonstrates the high sensitivity of this new FMBD module.

To further exploit the capability of the FMBD for higher data rate transmission, 16-QAM modulation scheme is employed for the IF envelope detection, while an arbitrary waveform generator (AWG) and a real-time oscilloscope (RTO) are adopted to generate and retrieve the IF signals in digital domain, respectively. Consequently, a highest baud rate of 12 Gbaud is achieved with a BER below the HD-FEC limit (2×10^{-3}) and an EVM of 11.9%, and the measured constellation diagram is shown in Fig. 3(b). This means 48 Gbit/s error-free transmission can be realized by employing a FEC at the receiver side to recover the data. It is noted that the data rate here is mainly limited by the imperfections of the optical sources, e.g., laser intensity noise, which can be further improved by introducing ultra-low-noise lasers.

B. Coherent detection

Due to the low barrier height resulting in a high sensitivity, the FMBD allows for a low LO power in coherent (homodyne and heterodyne) detections, which is beneficial for achieving a higher data rate given a certain RF power without reaching saturation. To this end, the homodyne detection experiment with OOK modulation scheme is carried out at 298 GHz, and the system setup is shown in Fig. 6. To obtain the optical signals with more stabilized phase, at the transmitter side, an electro-optic frequency comb generator is adopted, which consists of a single laser and two cascaded optical phase modulators driven by a millimetre-wave synthesizer at a frequency of 24.833 GHz (298 GHz/12). At the receiver side, a UTC-PD as a LO signal input is added, while a 3-dB waveguide coupler is introduced to combine the RF and LO signals with its output connected to the FMBD for IF signal demodulation as shown in Fig. 7. Furthermore, to synchronize the phase of RF and LO signals, an optical delay line is used to adjust the LO signal.

Initially, the BER against the transmitter power at a data rate of 15 Gbit/s is measured, while various LO power is applied. As shown in Fig. 8(a), by increasing the LO power, the BER curve is shifted to the left along the x-axis with a lower RF power required to achieve an error-free transmission, which suggests that the FMBD sensitivity is increased by injecting the LO power. In addition, given a constant LO injection power as -15 dBm (31.6 μW), the BERs against the transmitter power at four data rates are measured. As shown in Fig. 8(b), an error-free transmission is achieved at a data rate of 25 Gbit/s with the transmitter power of -18 dBm (15.8 μW). However, at 32 Gbit/s, it is challenging to achieve the error-free transmission even by further increasing the transmitter power. This is mainly due to the saturation effect of the FMBD module, which can be improved by optimizing the diode structure. The eye diagrams at different data rates are shown in Fig. 9, which have a clear openness at lower data rates and becomes noisy at 32 Gbit/s, corresponding to the BER results shown in Fig. 8(b). Nevertheless, as compared in Table 1, this SiC-substrate-based FMBD has the best communication performance ever reported with FMBD receivers.

To further verify the sensitivity of the FMBD, IF output power of the FMBD is measured by varying the transmitter power for both direct and coherent detections. Here, the LO injection power from the UTC-PD is -15 dBm, while the actual power input into the FMBD is at least 3 dB lower considering the 3-dB waveguide coupler effects. The measured results are shown in Fig. 10, where the FMBD has a higher sensitivity with LO power injected and starts to be saturated with a transmitter power of around -13 dBm. The saturation is supposed to be mainly caused by the output-limiting function of the internal TIA of the FMBD module.

Table 1. Comparison of highest communication data rate for various diodes (BER: bit error rate)

THz detector	OOK (Direct detection)	OOK (Coherent detection)	16-QAM (Direct detection)
SBD[a] [8]	12.5 Gbit/s (BER $= 10^{-4}$)	–	–
Quasi-optic FMBD [8]	12.5 Gbit/s (BER $= 10^{-9}$)	12.5 Gbit/s (BER $< 10^{-11}$)	–
Waveguide-input FMBD [9]	32 Gbit/s (BER $= 10^{-4}$)	32 Gbit/s (BER $= 2 \times 10^{-3}$)	–
This work	32 Gbit/s (BER $< 10^{-11}$)	32 Gbit/s (BER $= 10^{-7}$)	48 Gbit/s (BER $< 2 \times 10^{-3}$)

[a] The SBD is unbiased for fair comparison, while a maximum error-free data rate over 40 Gbit/s has been achieved for a biased SBD [3].

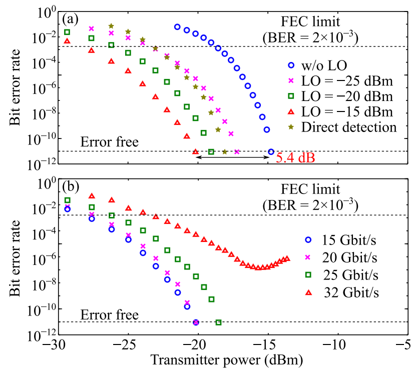

Fig. 8. Measured results for the homodyne detection with OOK modulation. Measured bit error rate (a) with various LO injection power at a data rate of 15 Gbit/s, and (b) at various data rates with LO power fixed as -15 dBm. The RF frequency for both measurements is 298 GHz.

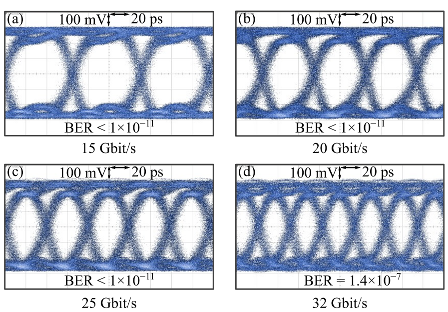

Fig. 9. Demodulated eye diagrams for the coherent detection at various data rates. Transmission data rate of (a) 15 Gbit/s, (b) 20 Gbit/s. (c) 25 Gbit/s, and (d) 32 Gbit/s.

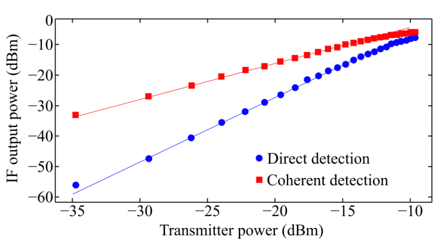

Fig. 10. Measured IF output power of the FMBD versus the transmitter power for both direct (envelope) and coherent (homodyne) detections at 298 GHz. The LO power for the coherent detection is selected as -15 dBm.

IV. Conclusion

A SiC-substrate-based Fermi-level managed barrier diode (FMBD) has been characterized and applied in 300-GHz band wireless communications with envelope and homodyne detections. The experimental results show that the FMBD has a IF bandwidth around 26 GHz at 300-GHz band. For the OOK modulation, an error-free transmission has been achieved at a data rate of 32 Gbit/s for the direct detection, and 25 Gbit/s for the coherent detection mainly due to the FMBD saturation effect. Limited by the optical sources, a below FEC-limit data rate of 48 Gbit/s is obtained for the direct detection with 16-QAM modulation scheme. It can be foreseen that such a high-sensitivity terahertz detector can benefit the beyond-5G communications with high transmission data rate at large.

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