Low noise homodyne detection of terahertz waves by zero-biased InP/InGaAs Fermi-level managed barrier diode

Hiroshi Ito\(^1,\(^{2a}\)\) and Tadao Ishibashi\(^3\)

\(^1\) Center for Natural Sciences, Kitasato University
\(^2\) Graduate School of Medical Sciences, Kitasato University,
1–15–1 Kitasato, Minami-ku, Sagamihara, Kanagawa 252–0373, Japan
\(^3\) NTT Electronics Techno Co.,
3–1 Morinosato Wakamiya, Atsugi, Kanagawa 243–0198, Japan
\(^a\) h.ito@kitasato-u.ac.jp

Abstract: Homodyne detection of terahertz (THz) waves by a zero-biased Fermi-level managed barrier (FMB) diode was investigated for the first time to reveal its fundamental characteristics in the mixing detection. The lowest noise equivalent power of \(1.6 \times 10^{-17} \text{ W/Hz}^{\frac{1}{2}}\) was obtained at 300 GHz with a very low local oscillator power of \(5 \times 10^{-7} \text{ W}\).

Keywords: THz wave, homodyne detection, noise equivalent power

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

References

[8] H. Ito and T. Ishibashi: “Fermi-level managed barrier diode for broadband and
1 Introduction

A low-noise terahertz (THz) wave detector is an important component for making sensitive measurements and having a wide dynamic range in various THz-wave systems. Among THz-wave detectors, the semiconductor diode-based THz-wave detector [1, 2, 3, 4] (either heterodyne detection or homodyne detection) is advantageous because of its low-noise and high-speed characteristics even at room temperature. The Schottky barrier diode (SBD), a typical and widely used THz-wave detector operated at room temperature, can also be used as a mixing detector. It has already realized noise equivalent powers (NEPs) more than two orders of magnitude lower than those obtained by the square-law detection of the SBD in the THz-wave range [2]. However, the SBD usually requires biasing or relatively large local oscillator (LO) input power for obtaining better noise characteristics [1, 3, 5, 6, 7] because of its relatively large barrier height.

Recently, we developed a novel InP/InGaAs hetero-barrier rectifier, called a Fermi-level managed barrier (FMB) diode [8, 9], to overcome the constraints associated with the Schottky barrier. The primary feature of the FMB diode is its very low barrier height adjusted in accordance with the anode Fermi level, which effectively decreases diode differential resistance, achieving easier impedance matching, and increasing output current, all at zero-biased operation. We have demonstrated a very low NEP of 3.0 pW/\sqrt{Hz} at 300 GHz in the square-law detection mode by using a zero-biased FMB diode [9]. In this study, we investigated homodyne detection using the zero-biased FMB diode for the first time in order to reveal its fundamental characteristics in the mixing detection of THz waves.

2 Experimental

Fig. 1 schematically shows the experimental setup for homodyne detection by the FMB diode. A mesa-structure FMB diode having a junction area of 0.4 µm², barrier height of about 70 meV, and an intrinsic differential resistance under a zero-biased condition of about 110 Ω was integrated with a broadband bowtie antenna [9]. Then, it was assembled in a quasi-optical package with a pre-amplifier and was zero-biased by being DC-blocked from the amplifier input node. The high-frequency electro-magnetic waves were generated by photomixing using two quasi-
optical uni-traveling-carrier photodiode (UTC-PD) modules [10]. One was used as an input signal source and the other as a LO signal source. An optical sinusoidal signal was generated by optical heterodyning using two laser diodes operating at around 1.55 µm. The signal was then amplified by an erbium-doped fiber amplifier (EDFA) and divided into two signals. An optical chopper was inserted into the measuring signal line for the lock-in detection. In contrast, an optical delay line was used in the LO signal line for varying the phase of the optical signal so that the phases of the measuring and LO signals fed to the FMB diode were adjusted to attain the maximum mixing efficiency. Transmitted signals were then combined at a THz-wave half mirror (Tydex, W-HRFZ-SI) and introduced to the FMB diode module. The output signal from the FMB diode was measured by a lock-in amplifier (Signal Recovery, 7270) with a time constant of 1 s. The chopping frequency was set to be about 1 kHz for suppressing the influence of 1/f noise. All the THz-wave powers described in this work are defined as a value in front of the FMB diode module and were calibrated using a power meter (VDI Ericsson, PM4).

3 Results and discussion

Fig. 2 shows the measured output voltages from the FMB diode module at 300 GHz against the input signal power ($P_s$) in the homodyne detection mode at room temperature (open symbols). The data for the square-law detection mode (closed circles) are shown for comparison. Here, several different LO power ($P_{LO}$) levels were tested. The output voltage for the homodyne detection mode increased in proportion to the square root of $P_s$ regardless of $P_{LO}$, which is the standard behavior of the homodyne detection mode [4]. In addition, the output voltage for the homodyne detection mode at a fixed $P_s$ increased in proportion to the square root of $P_{LO}$. These results confirm that the FMB diode acts as a mixer detector in the THz wave range.

To estimate the NEP of the FMB diode, the output noise voltage density of the module without supplying the input signal was measured by using the built-in function of the lock-in amplifier, and the results are illustrated as dashed lines in Fig. 2. Because the input LO signal created the diode current in the FMB diode, the noise voltage density started to increase at larger $P_{LO}$, as shown in Fig. 2.
the intersection of the extrapolated line for the output voltage tendency in homodyne detection mode and the dashed line for the noise voltage density gives the NEP at each $P_{\text{LO}}$. The NEP of the FMB diode in the square-law detection mode (without supplying the LO signal) was similarly obtained.

Fig. 3 shows the obtained NEP of the FMB diode module in the homodyne detection mode against $P_{\text{LO}}$ at 300 GHz. The NEP level obtained for the square-law detection mode (without supplying the LO signal) was similarly obtained.

Fig. 3 shows the obtained NEP of the FMB diode module in the homodyne detection mode against $P_{\text{LO}}$ at 300 GHz. The NEP level obtained for the square-law detection mode is also shown as a dashed line. The NEP was minimized at a $P_{\text{LO}}$ of

Fig. 3. Dependence of noise equivalent power (NEP) against local oscillator signal power at 300 GHz for homodyne detection mode. NEP level obtained for square-law detection mode is shown as a dashed line.
about $5 \times 10^{-7}$ W, and the resulting NEP was as low as about $1.6 \times 10^{-17}$ W/$\sqrt{\text{Hz}}$. This NEP value is more than five orders of magnitude lower than that of the square-law detection mode ($3 \times 10^{-12}$ W/$\sqrt{\text{Hz}}$) and is more than two orders of magnitude lower than the best NEPs reported for heterodyne detection by SBDs [2, 11]. In the low $P_{\text{LO}}$ region, the noise voltage density was almost constant and mainly determined by the thermal noise of the FMB diode and the integrated amplifier [9]. Thus, the NEP (input signal power at intersection point in Fig. 2) decreased with increasing $P_{\text{LO}}$ (which increases the output voltage). On the other hand, in the large $P_{\text{LO}}$ region, the noise originating from the optical source became prominent and the total noise voltage density increased with increasing $P_{\text{LO}}$. Thus, the NEP tended to show its minimum as $P_{\text{LO}}$ increased.

In the mixing detection mode, the output voltage is proportional to the product of $\sqrt{P_s}$ and $\sqrt{P_{\text{LO}}}$, while it is proportional to $P_{\text{LO}}$ in the square-law detection mode. The minimum detectable signal power in mixing mode ($1.6 \times 10^{-17}$ W at the optimum condition) was reached because supplied $P_{\text{LO}}$ ($5 \times 10^{-7}$ W) was much larger than $P_s$. Since the product $\sqrt{P_s} \times \sqrt{P_{\text{LO}}}$ at the optimum condition was comparable to the minimum detectable signal power in the square-law detection mode ($3 \times 10^{-12}$ W), the mixing operation of the FMB diode was considered to be quite efficient even under the zero-biased condition. More importantly, the optimum $P_{\text{LO}}$ obtained here is about three to four orders of magnitude lower than those reported by the zero-biased SBD mixers at room temperature [1, 3, 6, 7]. This large improvement is attributed to the large output current capability of the FMB diode under the zero-biased condition. Having a very low $P_{\text{LO}}$ is important for constructing an arrayed mixing detector since a single or small number of LO sources can deliver LO signals to a large number of detectors in an array. Furthermore, the extremely low NEP obtained in this study is considered to be applicable to passive THz-wave imaging of room-temperature objects. Thus, the FMB diode is a promising solution for low-noise THz-wave mixing detection.

4 Conclusion

We investigated homodyne detection of THz waves by using a zero-biased FMB diode module for the first time. Output voltage increased in proportion to both the square root of the input signal power and the square root of the LO input power in accordance with the homodyne detection mode. The minimum NEP obtained was as low as $1.6 \times 10^{-17}$ W/$\sqrt{\text{Hz}}$ at 300 GHz for a very low LO power of $5 \times 10^{-7}$ W.

Acknowledgments

The authors are grateful to I. Kotaka, S. Kusanagi, M. Shimizu, and H. Yamamoto for their valuable discussions. This work was supported in part by the Industry-Academia Collaborative R&D Program from the Japan Science and Technology Agency.