Continuous THz-Wave Generation using Uni-Traveling-Carrier Photodiode

Hiroshi Ito, Tomofumi Furuta, Fumito Nakajima, Kaoru Yoshino, and *Tadao Ishibashi

NTT Photonics Laboratories, NTT Corporation
3-1 Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-0198, Japan
*NTT Electronics Corporation, 1841-1 Tsuruma, Machida-shi, Tokyo 194-0004, Japan

Abstract

Photonic generation of millimeter/sub-millimeter waves up to THz range using an antenna-integrated uni-traveling-carrier photodiode is investigated. A test device measured on-wafer exhibits a record maximum output-power of 2.6 μW at 1.04 THz with good linearity. A quasi-optical module fabricated for practical use generates almost the same output power as the chip at around 1 THz and operates at frequencies of up to 1.5 THz. These are record results for photonic THz-wave generation using photodiodes operating at 1.55 μm.

Introduction

The generation of continuous millimeter(mm)/sub-mm wave signals using photonics technology is promising for various applications, such as high-speed measurements, spectroscopy, and the local signal supply for radio telescopes [1]. Among the photomixers that can generate such high-frequency signals, a photoconductive switch utilizing low-temperature-grown GaAs (LT-GaAs) is the most widely used. To date, sub-mm wave generation at up to 5 THz [2] has been reported using such a device. Although the response is very fast, this device utilizes short-wavelength ($\lambda \approx 0.8$ μm) light signal. Thus, it cannot use the abundant optical components developed for optical communications systems. A more convenient approach is to use a standard photodiode (PD) operating at a long-wavelength ($\lambda \approx 1.55$ μm). This enables us to use various optical components, such as optical fiber amplifiers and wavelength-tunable lasers. Sub-mm wave generation at up to 1 THz has already been reported using a conventional pin-PD [3]. A problem with this approach is that a conventional pin-PD has the inevitable trade-off between output and bandwidth [4]. In fact, the obtained output powers at around 1 THz are only a few nW [3], which has to be increased for practical applications.

The uni-traveling-carrier photodiode (UTC-PD) [5] is one of the best ways to improve the output power because it provides a high 3-dB down bandwidth (f_{3dB}) [6] and a high-saturation-output power [7] simultaneously. An output power of 300 μW at 300 GHz [8] has already been demonstrated for an antenna-integrated UTC-PD chip [9]. In the present work, we have investigated a photonic mm/sub-mm wave generation from a UTC-PD integrating a planar log-periodic antenna to demonstrate the possibility of practical output power in the THz range. A quasi-optical UTC-PD module [10] was also fabricated and its characteristics compared with that of the chip.

Device fabrication

The epi-layers were grown by MOCVD. The absorption layer consists of p-InGaAs ($p = 4 \times 10^{17}$ /cm^3, 80 nm), p-InGaAs ($p = 1 \times 10^{18}$ / cm^3, 10 nm) and undoped InGaAs (8 nm), and the collection layer consists of undoped InGaAsP (16 nm), undoped InP (6 nm), n-InP ($n = 1 \times 10^{18}$ /cm^3, 7 nm) and n-InP ($n = 1 \times 10^{16}$ /cm^3, 253 nm). Double-mesa back-illuminated UTC-PDs with an absorption area of 13 m m^2 were fabricated by wet chemical etching and metal-lift-off processes. Each PD was then integrated with a planar antenna on a semi-insulating InP substrate. Figure 1 shows a micrograph of the fabricated device. The device integrates a UTC-PD and a self-complementary log-periodic toothed planar antenna, whose teeth correspond to frequencies from 150 GHz to 2.4 THz. The p- and n-type electrodes of the PD were connected to each wing of the antenna. The front side of the wafer was anti-reflection coated, and the backside, high-reflection coated. The intrinsic f_{3dB} of a fabricated UTC-PD was evaluated to be 170 GHz by pulse photoresponse measurements, and its CR-limited bandwidth was estimated to be 210 GHz. The responsivity was measured to be about 0.03 A/W.

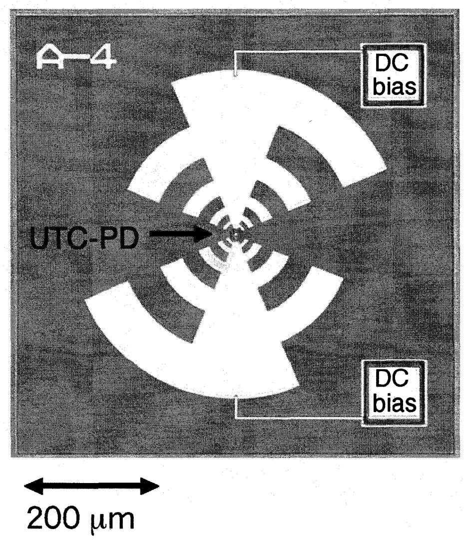

Fig. 1. Micrograph of the fabricated UTC-PD chip integrating a log-periodic toothed antenna.

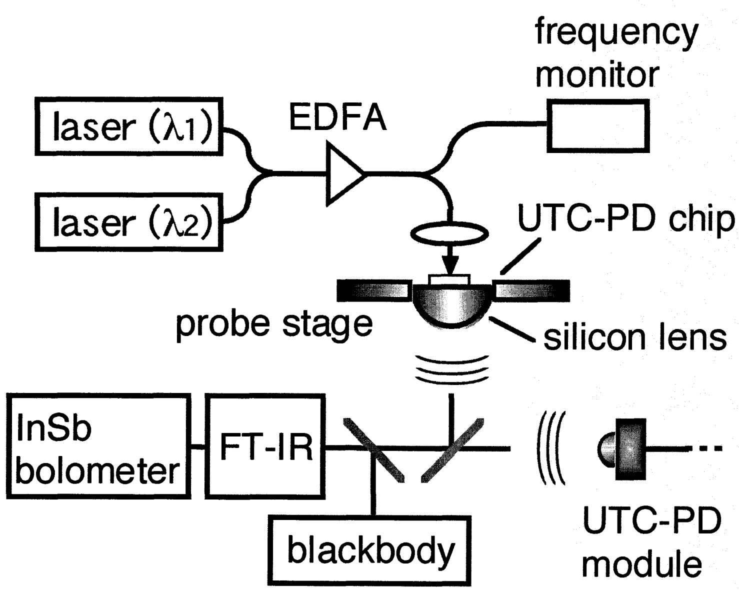

Fig. 2. Schematic drawing of the measurement setup.

Characterization

Figure 2 shows the experimental setup. The RF modulated optical signal was prepared by two-mode beating using two wavelength-tunable laser-diodes (WT-LDs) having λ_1 and λ_2 of around 1.55 μm. The optical modulation index of the optical signal measured was about 60 %. The device was placed on a hyper-hemispherical Si lens and measured on-wafer. The input optical signal introduced from the front side of the wafer was reflected at the backside, and then focused on the PD. The mm-wave was mainly emitted toward the backside of the wafer through the Si lens. The mm-wave power was alternately detected with a Schottky diode detector (Farran Technology, WD-03) with a feed-horn or with a Martin-Puplett-type Fourier transform spectrometer and InSb hot-electron bolometer. The absolute value of the output power was calibrated against blackbody. By using the same setup, we measured the output power from the module, so that we could quantitatively compare the output powers from both types of devices.

Experimental Results

Figure 3 shows the relationship between the measured mm-wave output power and the diode photocurrent for the device at 300 GHz for a bias voltage of -1.5 V. A wide linearity range is maintained up to a high output power of over 100 mW, and the saturated output power was 300 mW at a photocurrent of 20 mA. To our knowledge, this is the highest output-power directly generated from a PD in the 300-GHz band. Here, power losses due to the coupling efficiency of the horn antenna, absorption, reflection and divergence of the output signal, etc. were not excluded. Thus, the actual emitted power should be even higher.

Figure 4 shows the relationship between the measured output power and the photocurrent at 1.04 THz for a bias voltage of -2 V. Again, the output power increased linearly in proportion to the square of the photocurrent, and the maximum output power obtained was 2.6 μW at a photocurrent of 13 mA [10]. To our knowledge, this is also the highest output-power directly generated from a PD in the THz range. It is even higher than the highest output power reported for the LT-GaAs photoconductive switch [11] and more than two orders of magnitude higher than that obtained by a pin-PD [3]. The observed result includes power losses so that the actual emitted power should be even higher. More importantly, the bias voltage applied was about an order smaller than that required for the LT-GaAs photoconductive switch [2, 11]. Thus, the total power dissipation in the device is much smaller, which should be advantageous in regard to device reliability.

For practical use, we also fabricated the quasi-optic UTC-PD module shown in Fig. 5. We designed the module to be the same size as that of conventional semiconductor optoelectronic (O/E) devices [12] so that we could use standard assembly equipment. The PD chip was placed on a hyper-hemispherical silicon lens and electrically connected to the DC bias leads. Then, the photodiode was optically coupled to the optical fiber using a single-lens system. These optical parts were welded onto the package using a YAG laser, which assures the stability of the optical alignment. The size of the module is 12.7 mm × 30 mm × 10 mm (excluding the optical fiber and the leads).

Figure 6 shows the relationship between the detected output power and the photocurrent at 1.04 THz for a bias voltage of -0.75 V. The output power increased linearly in proportion to the square of the photocurrent, and the maximum output power obtained was 2.3 μW at a photocurrent of 13 mA. This is also the highest output-power directly generated from a PD module in the THz range. Noteworthy too is that the output power from the module is almost the same as that from the chip. This indicates that there is very small power penalty regarding the device assembly.

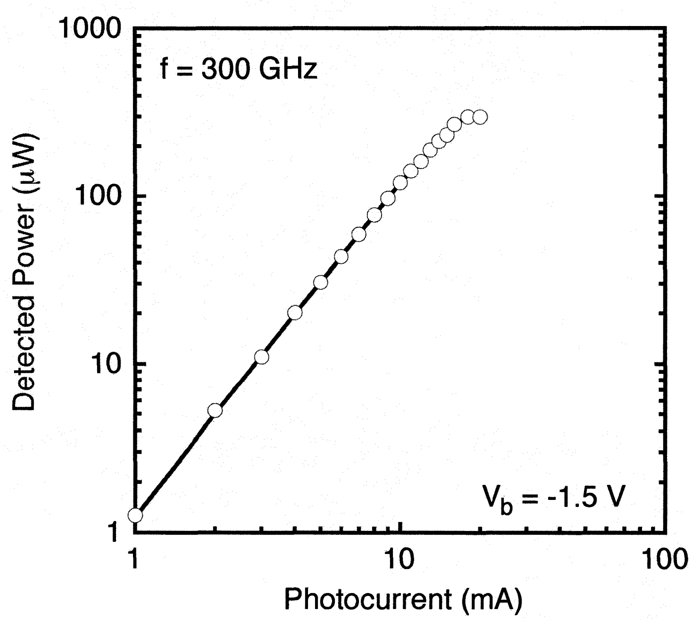

Fig. 3. Relationship between the measured mm-wave output power at 300 GHz and diode photocurrent for the antenna-integrated UTC-PD chip.

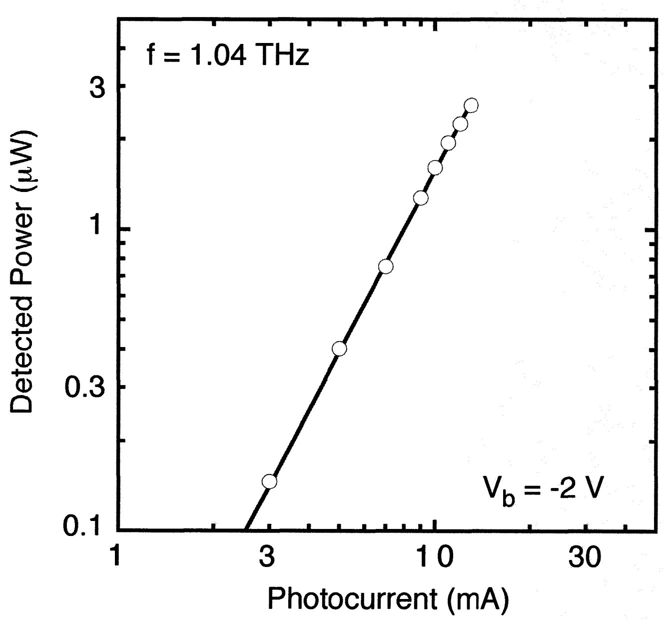

Fig. 4. Relationship between measured THz-wave output power and diode photocurrent for the UTC-PD chip.

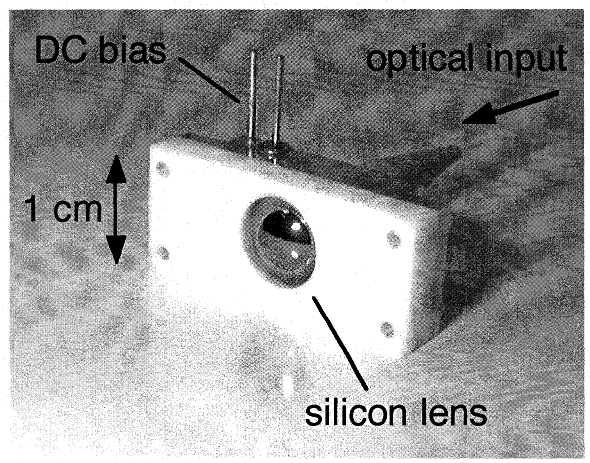

Fig. 5. Photograph of the fabricated quasi-optical UTC-PD module.

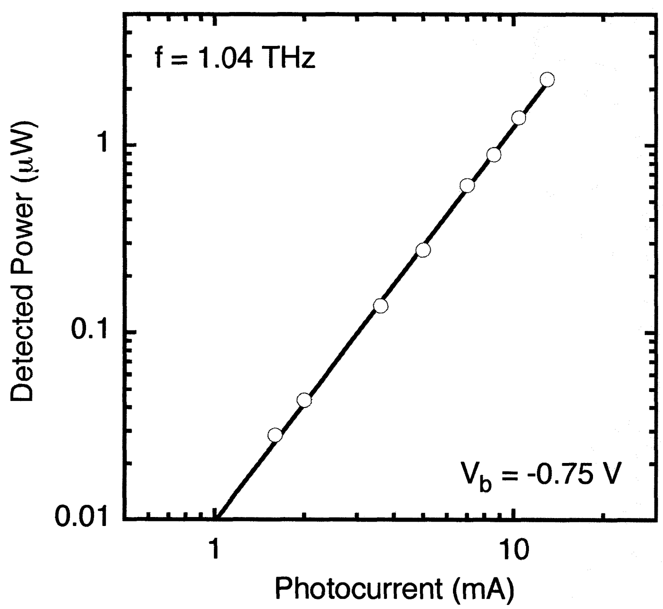

Fig. 6. Relationship between measured THz-wave output power and diode photocurrent for the quasi-optic UTC-PD module.

Figure 7 shows the frequency characteristics of the fabricated module for a photocurrent of 10 mA. The output power decreased gradually with increasing frequency, and we could detect sub-millimeter waves at frequencies of up to 1.5 THz. This is the highest operation frequency ever achieved by using a photodiode operating at 1.55 μm. The solid curve in the figure is a calculation, which only takes into account the CR-limited and transit-time limited bandwidths [9] of the UTC-PD with a constant loss. The experimental result agrees well with the calculation, indicating that only the device parameters of the PD are determining the basic frequency dependence and that the integrated antenna is very wideband. Thus, if we can eliminate the influence of the CR time constant by employing a resonating narrow-band matching circuit, it will be possible to obtain an output power of more than 10 μW at 1 THz, as indicated by the broken curve in the figure.

Figure 8 compares reported RF output powers above the 100-GHz range for UTC-PDs [8, 10, 12], pin-PDs [3, 13, 14], and LT-GaAs photomixers with a wideband design [11, 15]. The output power of a pin-PD has been reported to be inversely proportional to the fourth power of the frequency [3]. Although the results for UTC-PDs plotted in Fig. 8 are not for the same device, they well follow the trend for pin-PDs. More importantly, the output powers of UTC-PDs are about two orders of magnitude higher than those of pin-PDs, mostly due to their very high output saturation levels. The reason for the high output saturation level is that the space charge effect is less significant in a UTC-PD than in a pin-PD due to the difference in the accumulated carriers (electrons or holes). Moreover, the output power is even higher than those reported for LT-GaAs photomixers [11, 15]. These results clearly indicate that the UTC-PD is a promising and realistic device for generating a continuous THz wave with a practical output power, which is required in various applications.

Summary

We have investigated the generation of mm/sub-mm-waves at frequencies of up to the THz range by using an antenna-integrated UTC-PD. The fabricated device exhibits a record output power of 300 μW at 300 GHz and 2.6 μW at 1.04 THz, both with a good linearity. A quasi-optic module, which is the same size and has the same configuration as conventional O/E device modules, was also fabricated. The module exhibited output power similar to that of the chip, indicating the feasibility of the quasi-optic module. It could be operated at up to 1.5 THz, which is the highest operation frequency ever reported for the PDs operating at 1.55 μm. These results clearly demonstrate that the antenna-integrated UTC-PD is highly promising for use as a photonic mm-/sub-mm-wave generator in various practical applications in the THz range, such as sub-mm-wave spectroscopy, imaging, and a photonic local oscillator system in radio telescopes.

Acknowledgments

The authors thank T. Nagatsuma for his valuable discussions on the measurements, J. Yumoto and Y. Yoshikuni for their continuous encouragement, and Prof. M. Ishiguro of the National Astronomical Observatory of Japan for his stimulating discussions on photonic mm-wave sources.

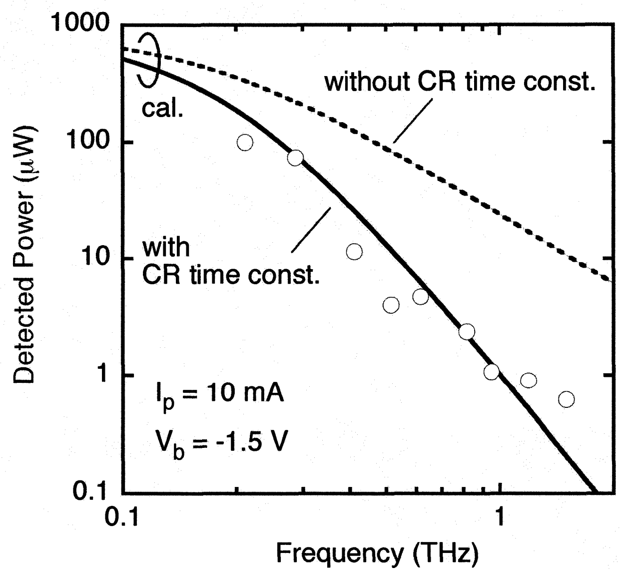

Fig. 7. Relationship between measured mm-/sub-mm-wave output power and frequency for the UTC-PD module.

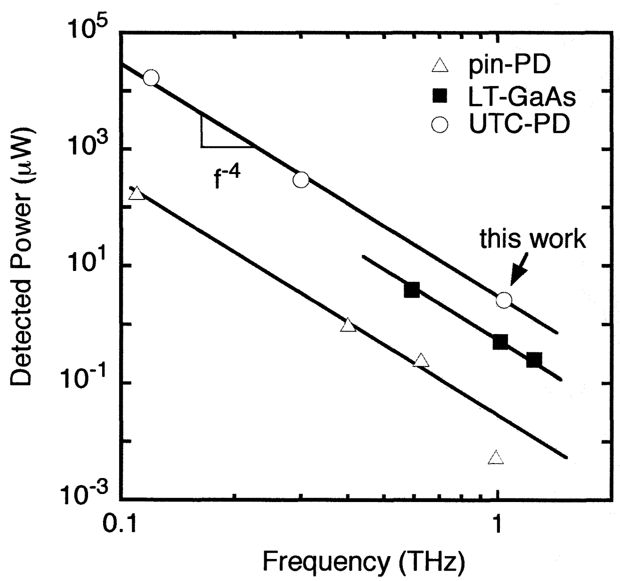

Fig. 8. Comparison of reported mm-/sub-mm-wave output power against the operation frequency for UTC-PDs, pin-PDs, and LT-GaAs photomixers.

References

[1] J. Payne, B. Shillue, and A. Vaccari, "Photonic techniques for use on the Atacama large millimeter array," Tech. Dig. Int. Topical Meeting on Microwave Photonics, pp. 105-108, 1999.

[2] K. A. McIntosh, E. R. Brown, K. B. Nichols, O. B. Mcmahon, W. F. Dinatale, and T. M. Lyszczarz, "Terahertz photomixing with diode lasers in low-temperature-grown GaAs," *Appl. Phys. Lett.*, vol. 67, pp. 3844-3846, 1995.

[3] A. Malcoci, A. Stöhr, S. Schulz, and D. Jäger, "Optical THz generation," Tech. Dig. Int. Topical Meeting on Microwave Photonics, pp. 179-182, 2003.

[4] K. Kato, S. Hata, K. Kawano, and A. Kozen, "Design of ultrawide-band, high-sensitivity p-i-n photodetectors," *IEICE Trans. Electron.*, vol. E76-C, pp. 214-221,1993.

[5] T. Ishibashi, N. Shimizu, S. Kodama, H. Ito, T. Nagatsuma, and T. Furuta, "Uni-traveling-carrier photodiodes," Tech. Dig. Ultrafast Electronics and Optoelectronics, pp. 83-87, 1997.

[6] H. Ito, T. Furuta, S. Kodama, and T. Ishibashi, "InP/InGaAs uni-travelling-carrier photodiode with 310 GHz bandwidth," *Electron. Lett.*, vol. 36, pp. 1809-1810, 2000.

[7] H. Ito, T. Nagatsuma, A. Hirata, T. Minotani, A. Sasaki, Y. Hirota, and T. Ishibashi, "High-power photonic millimetre-wave generation at 100 GHz using matching-circuit-integrated uni-travelling-carrier photodiodes," *IEE Proc. Optoelectron.*, vol. 150, pp.138-142, 2003.

[8] H. Ito and T. Nagatsuma, "High-speed and high-output-power uni-traveling-carrier photodiodes," Proc. SPIE, No. 4999, pp. 156-166, 2003.

[9] H. Ito, T. Furuta, Y. Hirota, T. Ishibashi, A. Hirata, T. Nagatsuma, H. Matsuo, T. Noguchi, and M. Ishiguro, "Photonic millimeter-wave emission at 300 GHz using an antenna-integrated uni-travelling-carrier photodiode," *Electron. Lett.*, vol. 38, pp. 989-990, 2002.

[10] H. Ito, F. Nakajima, T. Furuta, K. Yoshino, Y. Hirota, and T. Ishibashi, "Photonic terahertz-wave generation using an antenna-integrated uni-travelling-carrier photodiode," *Electron. Lett.* vol. 39, pp. 1828-1829, 2003.

[11] S. Verghese, K. A. McIntosh, S. M. Duffy, and E. K. Duerr, "Continuous-wave terahertz generation using photomixers," in *Terahertz Sources and Systems*, edited by R. E. Miles, P. Harrison, and D. Lippens, Kluwer Academic Publishers, Netherlands, pp. 157, 2001.

[12] H. Ito, T. Ito, Y. Muramoto, T. Furuta, and T. Ishibashi, "Rectangular waveguide output uni-traveling-carrier photodiode module for high-power photonic millimeter-wave generation in the F-band," *IEEE J. Lightwave Tech.*, vol. 21, pp. 3456-3462, 2003.

[13] P. G. Huggard, B. N. Ellison, P. Shen, N. J. Gomes, P. A. Davis, W. P. Shillue, A. Vaccari, and J. M. Payne, "Efficient generation of guided millimeter-wave power by photomixing," *IEEE Photonics Technol. Lett.*, vol. 14, pp. 197-199, 2002.

[14] P. G. Huggard, B. N. Ellison, P. Shen, N. J. Gomes, P. A. Davis, W. P. Shillue, A. Vaccari, and J. M. Payne, "Generation of millimetre and sub-millimetre waves by photomixing in 1.55 mm wavelength photodiode," *Electron. Lett.*, vol. 38, pp. 327-328, 2002.

[15] S. M. Duffy, S. Verghese, K. A. McIntosh, A. Jackson, A. C. Gossard, and S. Matsuura, "Accurate modeling of dual dipole and slot elements used with photomixers for coherent terahertz output power," *IEEE Trans. Microwave Theory and Tech.*, vol. 49, pp. 1032-1038, 2001.