Uni-Travelling-Carrier Photodiode Module Generating 300 GHz Power Greater Than 1 mW

Ho-Jin Song, *Member, IEEE*, Katsuhiro Ajito, *Member, IEEE*, Yoshifumi Muramoto, Atsushi Wakatsuki, Tadao Nagatsuma, *Senior Member, IEEE*, and Naoya Kukutsu, *Member, IEEE*

***Abstract*—In this letter, we demonstrate over 1 mW power generation at 300 GHz with a uni-travelling-carrier photodiode (UTC-PD) packaged in a WR-3 waveguide module. To increase the maximum power, two identical UTC-PDs were monolithically integrated along with a T-junction to combine the power from the two PDs. The UTC-PD module exhibited peak saturated output power of approximately 1.2 mW at 300 GHz with photocurrent of around 20 mA per PD and bias voltage of -3.9 V. In addition, 3 and 10 dB bandwidths were measured to be around 70 GHz or 23% and over 150 GHz or 50%, respectively.**

***Index Terms*—Millimeter-wave, terahertz (THz) wave, T-junction power combiner, uni-travelling-carrier photodiode (UTC-PD) module.**

I. INTRODUCTION

IN the last couple of decades, terahertz (THz) waves in the range from 100 GHz to 10 THz have been attracting a great deal of interest for use in bio-medical, pharmaceutical, security, sensing, and communications applications because of their unique features, such as their ability to penetrate many nonmetallic materials, spectroscopic fingerprints of molecules, and wide bandwidth [1]–[3]. For THz applications, several different types of signal sources are available. A frequency multiplier chain, which is a combination of frequency doublers and triplers based on Schottky barrier diodes or heterostructure barrier varactor, can generate up to a few ten mW at around 300 GHz [4]. Fundamental oscillators fabricated with THz transistors such as high electron mobility transistors (HEMTs) and heterojunction bipolar transistors (HBTs) have respectively demonstrated output power of 46 μW (or -13.4 dBm) at 314 GHz [5] and around 240 μW (or -6.2 dBm) at 310 GHz [6]. Though the power from the oscillators is not so high, THz transistors can amplify the signal to a few mW [7] in the 300 GHz band.

In addition to technologies based on the solid-state devices, photomixing devices, such as photodiodes and photoconductive switches, can be used for THz applications as well. These devices can utilize the advantages of photonic technologies, such as large operating bandwidth and the ability to transmit and manipulate THz signals with very low loss regardless of frequency [8]–[10]. These features enable us to share local oscillator signals at THz frequencies between large array radio astronomy antennas or to implement simple remote antenna stations with a photomixer for THz communications in the radio-on-fiber network configuration [10]. In addition, one can modulate the intensity, phase, and frequency of THz signals. Despite these merits, photomixer devices have seen limited use in THz applications because of their lack of power. State-of-the-art uni-travelling-carrier photodiodes (UTC-PDs), which are believed to provide higher power than other photomixers [8], [11], can produce just around 0.5 mW at 350 GHz [12] and 10.9 μW at 1 THz [8]. The heat problem is the biggest obstacle to improving the output power from a unit device further [8].

In this work, a power-combining technique for UTC-PDs, a popular approach in electronics for obtaining a higher power than a single device can provide, was adopted for UTC-PDs. Two UTC-PDs were monolithically integrated in parallel and their power was combined with an on-chip T-junction power combiner. The fabricated device was packaged in a WR-3 waveguide module. The UTC-PD module exhibited approximately 1.2 mW peak power at 300 GHz and 3 and 10 dB operation bandwidth of around 70 and 150 GHz, respectively.

II. UTC-PD MODULE

Basically, the core UTD-PD used in this work is identical to that described in [12], with the same epitaxial layers and device structure, but has a different matching circuit for different operating frequency at around 300 GHz. Two PDs were placed with 64 μm pitch in parallel, which is half of the fiber array pitch, 127 μm. To get the maximum output power at 300 GHz, the capacitance of the device was compensated with a CPW transmission line and short stub. To combine the power from the PDs, we used a T-junction. Though the T-junction doesn't provide isolation between two input ports and good matching at all ports simultaneously, the simple layout allows us to reduce radiation loss, which, if not reduced, would probably seriously affect the combining efficiency at these high frequencies. The T-junction consists of a $\lambda/4$-long 50 Ω coplanar waveguide (CPW) transmission line and air-bridges. Radiation loss was also taken into consideration when we selected the dimensions of the CPW. A wider signal line provides lower conduction loss, but electromagnetic energy can easily radiate into the air or couple to other modes, such as substrate modes, eventually resulting in larger total insertion loss. All CPWs in this work have 6.5 μm center

---

Manuscript received April 02, 2012; accepted May 04, 2012. Date of publication June 06, 2012; date of current version June 30, 2012.

H.-J. Song, K. Ajito, and N. Kukutsu are with the Microsystem Integration Laboratories, NTT Corporation, Atsugi, Kanagawa 243-0198, Japan (e-mail: song.hojin@lab.ntt.co.jp).

Y. Muramoto and A. Wakatsuki are with the Photonics Laboratories, NTT Corporation, Atsugi, Kanagawa 243-0198, Japan

T. Nagatsuma is with the Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka 560-8531, Japan.

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LMWC.2012.2201460

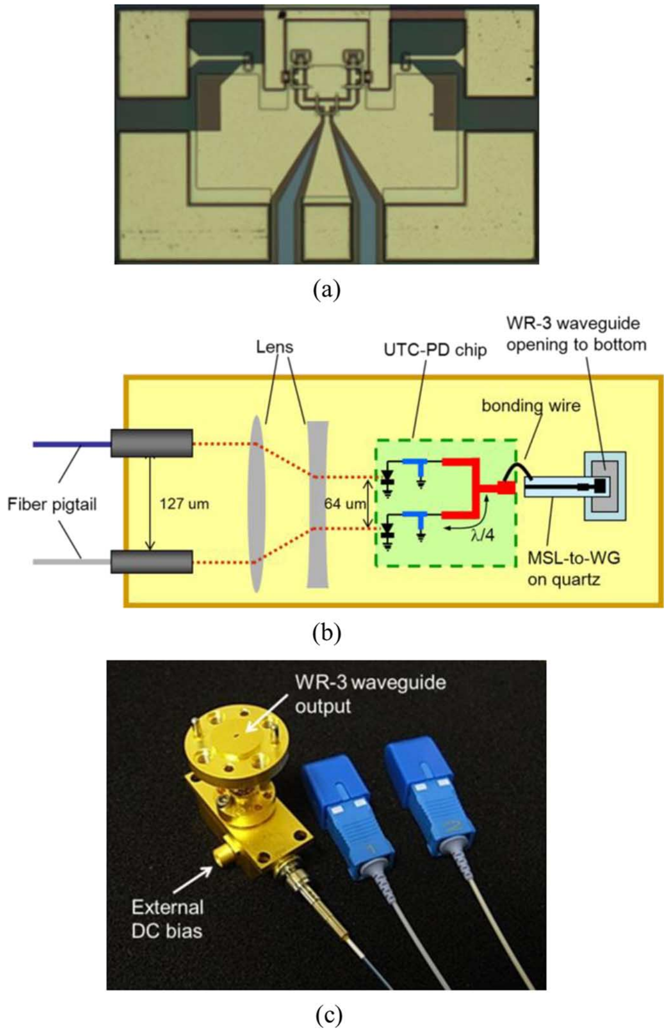

Fig. 1. (a) Top view of fabricated UTC-PDs with T-junction power combiner, (b) schematic diagram of package, and (c) photograph of the packaged module with two pigtailed fibers for the two UTC-PDs.

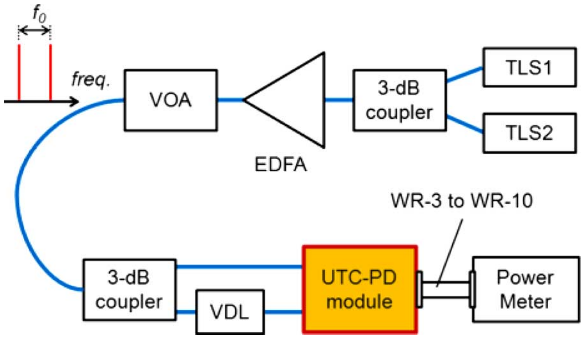

Fig. 2. Experiment setup (TLS: Tunable laser diode. EDFA: Er-doped fiber amplifier. VOA: Variable optical attenuator, VDL, Variable delay line).

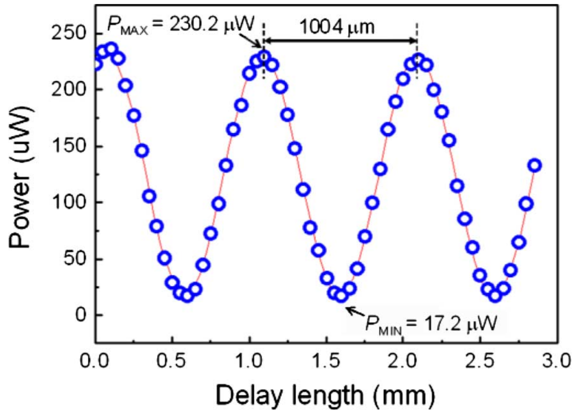

Fig. 3. Measured output power at 300 GHz with respect to delay length at fixed photocurrent.

line width and 4.5 μm gap. Full 3-D FEM and SPICE co-simulation was conducted with an equivalent circuit of the UTC-PD. Fig. 1(a) shows the top view of the fabricated UTC-PD chip.

Fabricated devices were put into WR-3 waveguide modules [13]. Fig. 1(b) shows a schematic diagram of the package. A pair of lens were used to collimate the light beams from the fiber array and adjust the pitch of the beams to 64 μm. Collimated beams were coupled to the UTC-PDs laterally. A waveguide coupler on the quartz substrate follows the UTC-PD chip. Fig. 1(c) shows a photograph of the UTC-PD module with a pigtailed fiber for each PD. DC responsivity of the packaged PDs was measured to be approximately 0.17 A/W for each.

III. RESULTS

The UTC-PD module was evaluated in terms of output power and operation bandwidth. Power was measured with a calibrated power meter (Erickson Power Meter PM4). Fig. 2 shows the experiment setup. Two tunable laser sources in the 1550 nm band were used to generate a single-frequency THz wave.

First, we examined whether the THz waves from the two PDs are being combined coherently or not. For this purpose, we inserted a variable optical delay line into one of the pigtailed fibers and measured output power at 300 GHz while varying the relative optical path length difference using the delay line. As shown in Fig. 3, a clear interference pattern was observed with respect to the delay length, which implies the THz signals from the two PDs are indeed combined coherently via the T-junction. From the curve fitting, the period of the power change was found to be 1004 μm, which is almost equal to the wavelength of 300 GHz signal. However, the minimum power didn't reach zero. This must be due to imbalances between the two signal paths for each PD, including the optical and electrical ones or the PDs themselves. This imbalance can be equivalently quantified as a 0.6 dB RF power difference or a 3.6% variation of responsivity between the PDs.

Next, output power at 300 GHz was measured with respect to the photocurrent per PD, and the result is shown in Fig. 4. Before the measurement, the optical delay line was adjusted so that the UTC-PD module would produce the maximum power. It can be seen that the trace plotted in Fig. 4 shows a little bit different relationship from that defined by theory, i.e., that the output power from a PD is proportional to the square of photocurrent. This is because the UTC-PDs have a bias dependency and the actual bias across the PDs varies with photocurrent at the fixed external bias voltage due to a voltage drop across the bias resistor used to protect the UTC-PDs. In this experiment, bias voltage from an external source was fixed to -3.9 V. As shown in Fig. 4, the saturated output power from the UTC-PD module reaches approximately 1.2 mW at the photocurrent of 20 mA per PD. To the best of our knowledge, this is the highest output

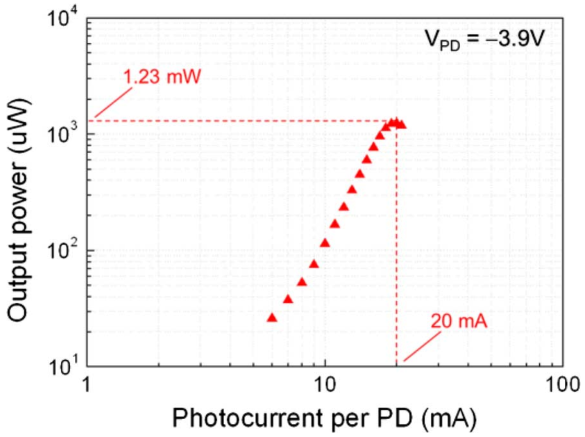

Fig. 4. Measured output power at 300 GHz with respect to photocurrent per PD.

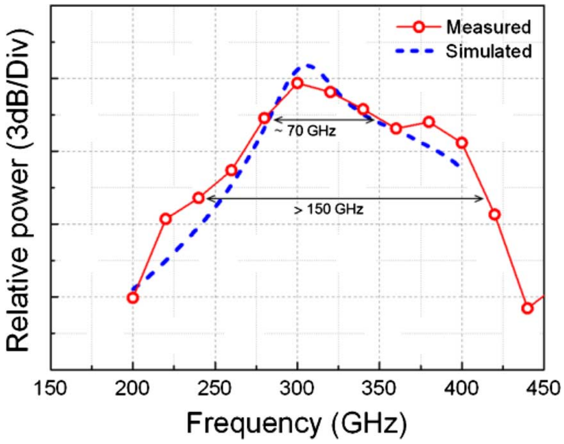

Fig. 5. Measured and simulated spectral characteristics.

power produced by any kind of photomixer device ever reported at this frequency. Note that the single PD module in [12], which utilizes the same UTC-PD, exhibits approximately 0.54 mW (−2.7 dBm) at 350 GHz at maximum. Though insertion loss of the T-junction was not directly measured in this work, the result implies the loss is quite small and further higher power up to 10 mW at 300 GHz band would be feasible by increasing the number of PDs and optimizing the core of the UTC-PDs further [8]. For practical use, the optical splitter, which was an external device in this work, should be integrated into the package or UTC-PD chip using optical planar circuit technologies.

Fig. 5 shows the measured and simulated spectral characteristics of the module. To maximize the output power, the optical delay line was tuned at every frequency step. The UTC-PD module offered the highest power at around the design frequency, 300 GHz, In addition, 3 and 10 dB operation bandwidths were found to be around 70 GHz or 23% and over 150 GHz or 50%, respectively, which is narrower than for the previous UTC-PD module [12] designed for slightly higher frequency. This must be due to the T-junction, which has its own frequency characteristics and results in a longer RF path in the UTC-PD chip.

IV. CONCLUSION

We presented a high-power UTC-PD module for THz-wave applications. To increase the maximum power, two identical UTC-PDs and a T-junction were monolithically integrated in a single chip and powers from the PDs were combined with the T-junction. The UTC-PD chip was packaged in a WR-3 waveguide module. The PD module exhibited peak saturated output power of greater than 1 mW at 300 GHz and photocurrent of 20 mA per PD. This is the highest power at this frequency ever produced by photomixers. Though the operating bandwidth was reduced due to the power combiner, the module still provides large enough bandwidth for some applications, such as THz noise imaging and communications.

ACKNOWLEDGMENT

The authors thank K. Aihara, T. Akeyoshi, M. Yaita, T. Ishibashi and S. Kodama for their support and K. Miyake and T. Takada for assistance in the experiments.

REFERENCES

[1] P. H. Siegel, “Terahertz technology,” *IEEE Trans. Microw. Theory Tech.*, vol. 50, no. 3, pp. 910–928, Mar. 2002.
[2] M. Tonouchi, “Cutting-edge terahertz technology,” *Nature Photon.*, vol. 1, pp. 97–105, Feb. 2007.
[3] H.-J. Song and T. Nagatsuma, “Present and future of terahertz communications,” *IEEE Trans. THz Sci. Technol.*, vol. 1, no. 1, pp. 256–263, Sep. 2011.
[4] G. Chattopadhyay, “Technology, capabilities, and performance of low power terahertz sources,” *IEEE Trans. THz Sci. Technol.*, vol. 1, no. 1, pp. 33–53, Sep. 2011.
[5] V. Radisic, X. B. Mei, W. R. Deal, W. Yoshida, P. H. Liu, J. Uyeda, M. Barsky, L. Samoska, A. Fung, T. Gaier, and R. Lai, “Demonstration of sub-millimeter wavefundamental oscillators using 35 nm InP HEMT technology,” *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 3, pp. 223–225, Mar. 2007.
[6] M. Seo, M. Urteaga, A. Young, V. Jain, Z. Griffith, J. Hacker, P. Rowell, R. Pierson, and M. Rodwell, “300 GHz fixed-frequency and voltage-controlled fundamental oscillators in an InP HBT process,” in *IEEE MTT-S Int. Dig.*, May 2010, pp. 272–275.
[7] L. A. Samoska, “An overview of solid-state integrated circuit amplifiers in the submillimeter-wave and THz regime,” *IEEE Trans. THz Sci. Technol.*, vol. 1, no. 1, pp. 9–24, Sep. 2011.
[8] T. Nagatsuma, H. Ito, and T. Ishibashi, “High-power RF photodiodes and their applications,” *Laser Photon. Rev.*, vol. 3, pp. 123–137, Mar. 2009.
[9] H.-J. Song, K. Oh, N. Shimizu, N. Kukutsu, and Y. Kado, “Generation of frequency-modulated sub-terahertz signal using microwave photonic technique,” *Opt. Express*, vol. 18, pp. 15936–15941, Jul. 2010.
[10] H.-J. Song;, K. Ajito, A. Wakatsuki, Y. Muramoto, N. Kukutsu, Y. Kado, and T. Nagatsuma, “Terahertz wireless communication link at 300 GHz,” in *Proc. IEEE Topical Meeting Microw. Photon.*, 2010, pp. 42–45.
[11] T. Ishibashi and H. Ito, “Uni-traveling-carrier photodiodes,” in *Proc. Ultrafast Electron. Optoelectron.*, 1997, pp. 83–87.
[12] A. Wakatsuki, T. Furuta, Y. Muramoto, T. Yoshimatsu, and H. Ito, “High-power and broadband sub-terahertz wave generation using a J-band photomixer module with rectangular-waveguide output port,” in *Proc. Int. Conf. Infrared, Millim. Terahertz Waves*, 2008, pp. 1–2.
[13] H. Ito, T. Furuta, Y. Muramoto, T. Ito, and T. Ishibashi, “Photonic millimetre- and sub-millimetrewave generation using J-band rectangularwaveguide-output uni-travelling-carrier photodiode module,” *Electron. Lett.*, vol. 42, no. 24, pp. 1424–1425, Nov. 2006.