Giga-bit Wireless Communication at 300 GHz Using Resonant Tunneling Diode Detector

Takeshi Shiode #1, Toshikazu Mukai *2, Masashi Kawamura #3, and Tadao Nagatsuma #4

#*Graduate School of Engineering Science, Osaka University*
1-3 Machikaneyama, Toyonaka, Osaka 560-8531, Japan
[1]shiode@laser.ee.es.osaka-u.ac.jp
[3]kawamura@laser.ee.es.osaka-u.ac.jp
[4]nagatuma@ee.es.osaka-u.ac.jp
**Photonics R&D Center, Research and Development Headquarters, Rohm Co., Ltd.*
21 Saiin Mizosaki-cho, Ukyo-ku, Kyoto 615-8585, Japan
[2]toshikazu.mukai@dsn.rohm.co.jp

Abstract — **We propose the use of a resonant tunneling diode (RTD) as a detector in terahertz wireless communications systems. Comparing to the conventional Schottky-barrier diode detector, the RTD is expected to provide about 30-dB increase in the sensitivity due to its strong nonlinearity. We have experimentally demonstrated an error-free wireless transmission at a bit rate of 2 Gbit/s using the RTD at 300 GHz.**

Index Terms —**Resonant tunneling devices, Diodes, Detectors, Wireless communication, Submillimeter wave communication.**

I. Introduction

Recently, there has been an increasing interest in the application of terahertz (THz) waves (0.1 THz~10 THz) to the high-speed wireless communications [1]. In particular, the use of frequencies above 275 GHz is one of the strong concerns among radio scientists and engineers, because these frequency bands have not yet allocated at specific applications, and there is a possibility to employ extremely large bandwidths for ultra-broadband wireless communications.

300-GHz band wireless link at a bit rate of over 10 Gbit/s has been reported, where a photonics-based transmitter and a Schottky-barrier diode detector are used [2], [3]. To bring the THz wireless communications technology to the consumer marketplace, the development of transmitter based on semiconductor electronic devices is urgently required. There are various candidates for electronic THz emitters or oscillators operating at room temperature such as tunnel transit-time (TUNNET) diodes, impact ionization avalanche transit-time (IMPATT) diodes, Gunn diodes, resonant tunneling diodes (RTDs), and transistor-based oscillators [4]. Among them, the RTD has exhibited the highest oscillation frequency at over 1 THz [5]. Mukai et al. recently introduced the RTD oscillator in the 300-GHz band electronic transmitter, and succeeded in the wireless transmission at 1.5 Gbit/s [6].

In addition to the application of RTDs to THz transmitters, the RTD is expected to be employed as a detector in the THz region due to its strong nonlinearity in the I-V characteristics. In this paper, we discuss and experimentally verify the use of the RTD as a highly-sensitive detector in the 300-GHz band wireless link. The device structure and characteristics are shown in Section II. Section III describes the experimental setup of the wireless transmission and the obtained results. Finally, we compare the sensitivity of RTD detector with that of commercially available Schottky barrier diode detector in Section IV.

II. Structure and Characteristics of RTD

Figure 1 shows an antenna integrated RTD device and a layer structure of the RTD. The RTD is integrated with a tapered slot antenna on InP substrate. This RTD chip is 3 mm long, 1.5 mm wide and 0.7 mm thick. The gain of the antenna is 10 dB. The RTD has a quantum well between two heterobarriers. Due to the potential well, the I-V characteristic of RTDs has a negative differential resistance (NDR) region [7].

The I-V characteristic of the RTD fabricated is shown in Fig. 2. This characteristic is before depositing a bismuth film which is connected between anode and cathode electrodes to suppress a parasitic oscillation at 2-3 GHz formed by external circuits including DC bias line. The NDR region can be seen between about 0.5 V and 0.8 V or between about -0.2 V and -0.4 V. The RTD device acts as an oscillator when biased in the NDR region [7].

Even when the RTD is biased in the normal resistance region outside the NDR, it still shows a strong nonlinearity as shown in Fig. 2. This nonlinearity is expected to be useful for a square-law detection. The output current, $I(V)$, is approximated by

$$I(V) = \frac{a^2}{4} \left. \frac{d^2 I}{dV^2} \right|_{V=V_0}, \qquad (1)$$

where a is an amplitude of the input voltage, d^2I/dV^2 is the second derivatives of the I-V characteristic at a bias point, V_0 [8].

From Eq. (1), the calculated sensitivity (intrinsic response) of the RTD with I-V characteristic of Fig. 2 is about 30 dB larger than that of conventional Schottky barrier diode. Usually, highest sensitivity is obtained when the RTD is biased close to the peaks of the NDR region, A and B, as indicated in Fig. 2.

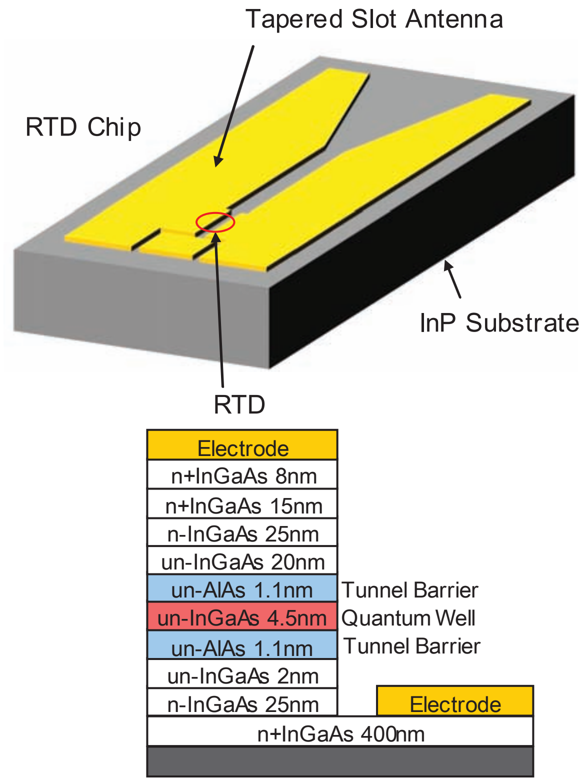


Fig. 1. The device and layer structures of the RTD.

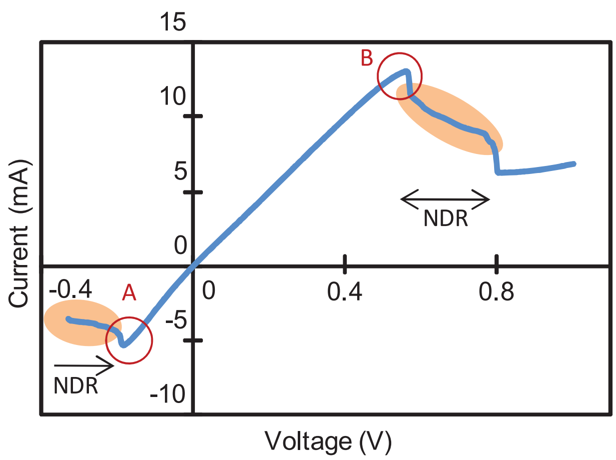


Fig. 2. The I-V characteristic of the RTD. Solid circles are bias points for the oscillator operation, and open circles for the detector operation.

Figure 3 shows a schematic of the packaged receiver. The RTD device is mounted on a coplanar line (CPW) fixture with a coaxial connector. By using a bias-T, DC voltage is applied to the RTD, and the output signal is extracted through the same CPW. The RTD chip and the CPW are connected by wire bonding.

The antenna directionality of this receiver is almost perpendicular to the surface of InP substrate as shown in Fig. 3. This is because the relative dielectric constant of the InP substrate is 12.1 and then the electromagnetic wave is gravitated into the thick substrate. Approximately 97% of the total output power is radiated toward the substrate in the case of oscillator [9].

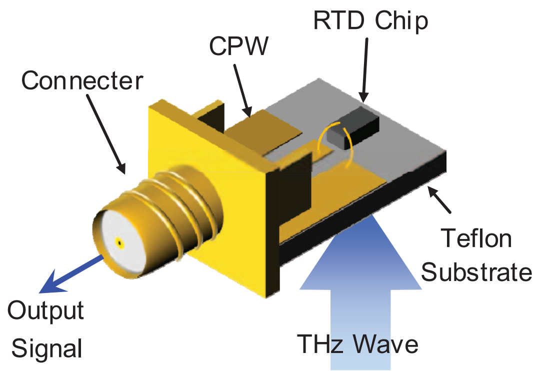


Fig. 3. Structure of the packaged receiver using the RTD chip.

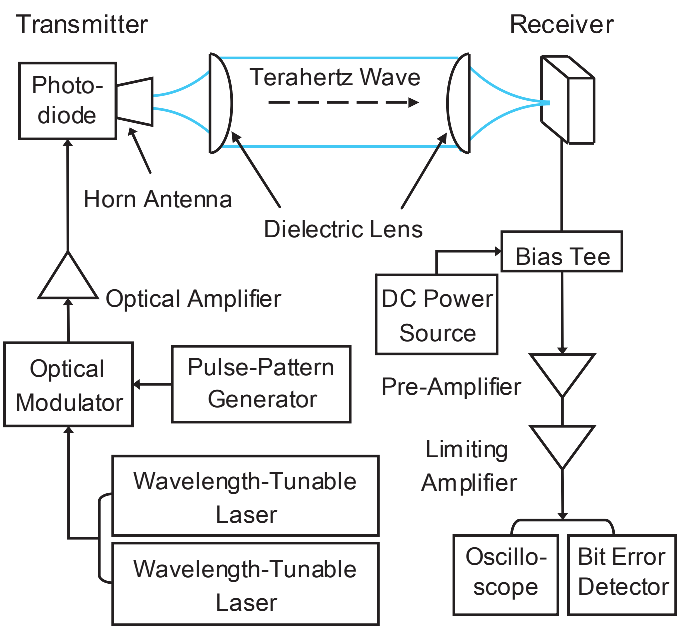


Fig. 4. Block diagram of 300-GHz band wireless link using the RTD as a detector. The transmitter is based on the photonic generation of THz signals using a photomixing technique.

III. Wireless Transmission Experiments

The experimental setup for the wireless transmission is shown in Fig. 4. In the transmitter, first the sinusoidally intensity-modulated optical signal at 300 GHz is generated by using two sets of wavelength tunable lasers with a wavelength difference of 2.4 nm, which corresponds to 300 GHz. Then, the optical signal is ON-OFF modulated with the optical intensity modulator, which is driven by the pulse pattern generator at a bit rate of >1 Gbit/s. Finally, the optical signal is converted to THz signal by the ultrafast photodiode [10].

In the RTD receiver, the detected THz signal is demodulated by the envelope detection, and the demodulated signal is amplified and reshaped by a pre-amplifier and a limiting amplifier, respectively.

In the experiment, we used two dielectric (Teflon) lenses for the transmitter and receiver to collimate and focus THz waves. The transmission distance was set to about 0.3 m, which is limited by the size of table on which components are placed.

Figure 5 shows the eye diagram at a bit rate of 1.5 Gbit/s, when the DC bias point was set to A in Fig. 2, typically 0.18 V. The output power from the transmitter was less than a few μW. The measured bit error rate (BER) was less than 10^{-11}, or an error free performance was confirmed. On the other hand, when the DC bias was set to B in Fig. 2, the obtained eye diagram became deteriorated, and the BER increased. This may be attributed to the increase of voltage/current noise with higher DC bias voltage.

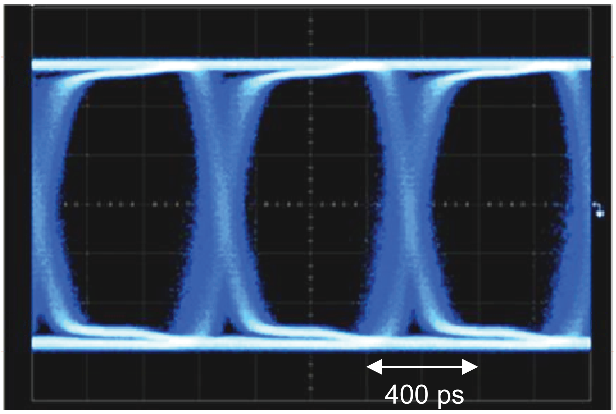


Fig. 5. The demodulated eye diagram at a bit rate of 1.5 Gbit/s with a carrier frequency of 300 GHz when the transmission distance is 0.3 m.

Figure 6 shows a relationship between the data rate and BER. An error-free transmission was achieved below 2 Gbit/s. This result is attributed to a bandwidth limitation of the pre-amplifier, which is around 1 GHz. So, the increase in the bit rate up to 10 Gbit/s will be feasible by increasing the bandwidth of the amplifier.

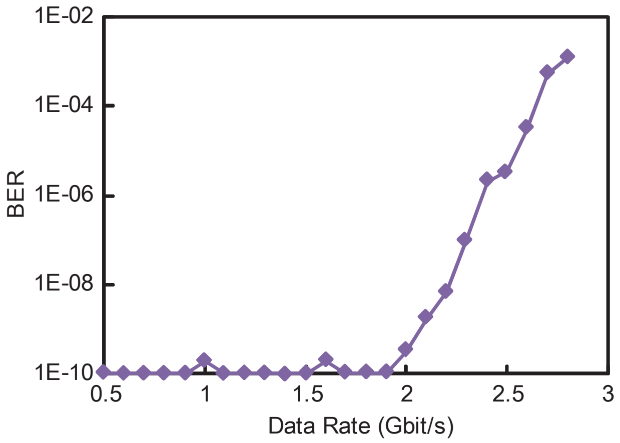


Fig. 6. Dependence of BER on the data rate.

IV. Comparison with Schottky Barrier Diodes

We compared our RTD detector with a conventional Schottky barrier diodes (SBD) detector to show a superior performance of the RTD detector with respect of sensitivity. The SBD detector used is commercial one (WR2.8ZBD) from Virginia Diode Inc. The SBD detector was assembled with a diagonal horn antenna with a gain of 25 dB. In this experiment, we removed dielectric lenses (Fig.4), and the horn antenna and the RTD detector were placed closer (a few mm).

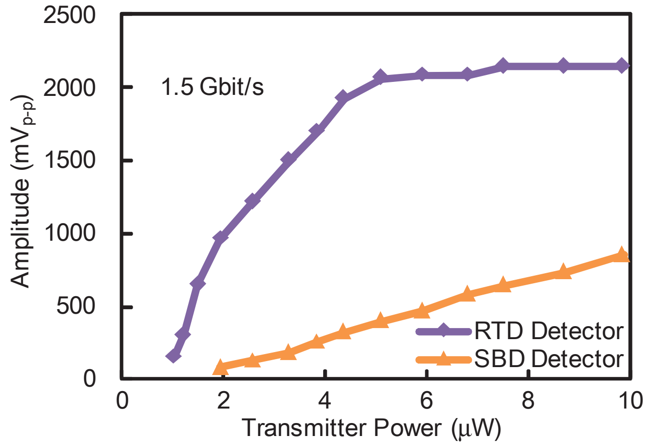
Figure 7 (a) compares the sensitivity between RTD and SBD detectors at a bit rate of 1.5 Gbit/s by measuring output voltages at the output port of the preamplifier.

As shown in Fig. 7 (a), the sensitivity of the RTD detector is higher (up to 12 dB) than that of the SBD under the transmitter power of 5 μW. Above 5 μW, the output of the pre-amplifier saturates to 2 V_{p-p}. The sensitivity of the RTD itself estimated from the DC I-V curve is about 30 dB higher than that of the SBD. However, the antenna gain of the RTD detector is about 15 dB lower than that of the SBD. We can estimate the signal loss of about 4 dB in the packaged RTD detector, particularly by the impedance mismatch at the wire bonding between the RTD chip and the CPW substrate (Fig. 3). This power loss of the RTD was experimentally evaluated by the time domain reflectometry.

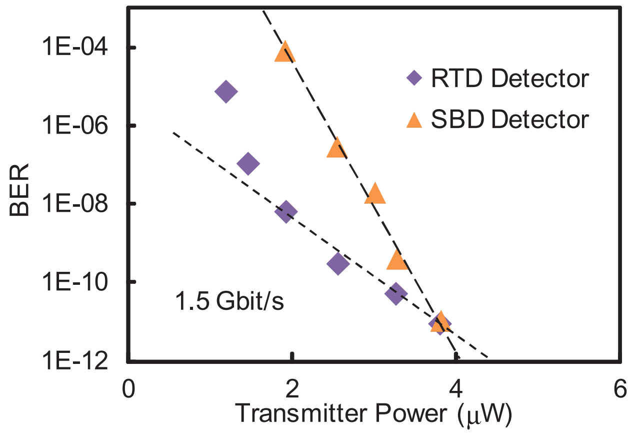
Table I summarizes the comparison between the RTD and SBD detectors with respect to antenna gain, sensitivity and loss. Considering these values, the difference in sensitivity is calculated to be 11 dB, which is in good agreement with the experimental one. It must be added that our antenna-integrated RTD detector is more compact and cost-effective. The packaged RTD has the sizes 20 × 10 × 8 mm, and the SBD has the size 44 × 32 × 20 mm.

Finally, we compare the relationship between the transmitter power and the BER for the RTD and SBD detectors in Fig. 7 (b). As expected, the RTD detector requires less transmitter power than the SBD detector above BER = 10^{-8}. But, the required transmitter power is almost the

same for the error-free (BER = 10^{-11}) condition. This may be caused by the signal deterioration due to the parasitic oscillation and impedance mismatch in the RTD detector. In general, the BER becomes very sensitive to the signal distortion as it approaches an error-free condition of less than 10^{-11}.



(a)



(b)

Fig. 7. Comparison of output voltages from a pre-amplifier (a), and BER characteristics (b) between RTD and SBD detectors.

TABLE I
COMPARISON OF PERFORMANCES

	SBD	RTD
Antenna Gain (dB)	25	10
Relative Intrinsic Detector Sensitivity (dB)	0 (reference)	~ 30
Power Loss (dB)	NA	~ -4
Experimental Detector Sensitivity (dB)	0 (reference)	< 12

V. CONCLUSION

We have demonstrated a wireless transmission at 300 GHz using the RTD as a detector. An error-free transmission up to 2 Gbit/s has been confirmed. In addition, we compared the sensitivity of the RTD detector integrated with a planar antenna to the commercially available Schottky barrier diode detector, and confirmed that the total responsivity of our RTD detector with a low-gain (10-dB) antenna was higher than that of the SBD with a high-gain (25-dB) horn antenna.

Future work addresses comparison of NEP with SBD, higher bit-rate detection and the wireless communication using the RTDs for both a transmitter and a receiver. If this is realized, it is expected that a half-duplex communication using one RTD chip will be realized.

ACKNOWLEDGEMENT

The authors wish to acknowledge Drs. K. Ajito, N. Kukutsu, H. –J. Song and A. Wakatsuki for their advice and comments. This work was supported in part by the JST-ANR WITH program.

REFERENCES

[1] M. Tonouchi, "Cutting-edge terahertz technology," *Nature Photonics,* vol. 1, no. 2, pp. 97-105, February 2007.

[2] T. Nagatsuma, H. –J.Song, Y. Fujimoto, A. Hirata, K. Miyake, K. Ajito, A. Wakatuki, T. Furuta, and N. Kukutsu, "Giga-bit wireless link using 300-400 GHz bands," *IEEE International Topical Meeting on Microwave Photonics 2009*, Th.2.3, Valencia, 2009.

[3] H. –J. Song, K. Ajito, A. Wakatsuki, Y. Muramoto, N. Kukutsu, T. Nagatsuma, and Y. Kado, "Terahertz-wave wireless communications link at 300 GHz," *Tech. Dig. Optical Terahertz Science and Technology 2011 Meeting*, MF42, Santa Barbara, 2011.

[4] M. Shur, "Terahertz Electronics," *CS MANTECH Conference*, Chicago, Illinois, April, 2008.

[5] S. Suzuki, M. Asada, A. Teranishi, H Sugiyama and H. Yokoyama, "Fundamental oscillation of resonant tunneling diodes above 1 THz at room temperature," *Applied Physics Letters*, vol. 97, no. 24, pp. 242102-242102-3, December 2010.

[6] T. Mukai, M. Kawamura, T. Takada, and T. Nagatsuma, "1.5-Gbps wireless transmission using resonant tunneling diodes at 300 GHz," *Tech. Dig. Optical Terahertz Science and Technology 2011 Meeting*, MF42, Santa Barbara, 2011.

[7] M. Asada, S. Suzuki, and N. Kishimoto, "Resonant tunneling diodes for sub-terahertz and terahertz oscillators," *Jpn. J. Appl. Phys.*, vol. 47, no. 6, pp. 4375-4384, 2008.

[8] G. H. Rieke, "Visible and infrared coherent receivers," in *Detection of light: from the ultraviolet to the submillimeter*, 2nd ed. Cambridge, United Kingdom: Cambridge University Press, ch. 10, sec. 1, pp. 275-279, 2003.

[9] T. Mukai, M. Asada, S. Suzuki, K. Urayama, "Terahertz oscillation device," *United States Patent,* no. 7,898,348, March 2011.

[10] T. Ishibashi, N. Shimizu, S. Kodama, H. Ito, T. Nagatsuma, and T.Furuta, "Uni-traveling-carrier photodiodes," *Ultrafast Electronics and Optoelectronics*, Nevada, March 17, 1997.