

# Resonant Tunneling Diode as High Speed Optical/Electronic Transmitter

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**Abstract**— We report both electronic and opto-electronic resonant tunneling diode (RTD) oscillators with relatively high output power. Electronic RTD oscillators working at 125/156/308 GHz with around one half milliwatt output power and optoelectronic oscillators in the 30 – 105 GHz range with about 1 mW output power at 44 GHz have been developed. First wireless transmission experiments with a 300 GHz oscillator are also reported.

**Keywords**—RTD; RTD-PD; Oscillator; terahertz; wireless communication

## I. INTRODUCTION

Terahertz (THz) technology has wide applications in such as security imaging, ultrafast wireless communication, spectroscopy systems, etc. [1]. Due to the lack of compact and high power THz sources operating at room temperature, the THz frequency is the less developed spectrum, especially in the 0.1 – 3 THz range. The resonant tunneling diode (RTD) has received considerable attention recently for realizing THz sources [2, 3]. Of all present solid-state sources, it has the highest demonstrated oscillation frequency of 1.92 THz [3]. Other advantages of the RTD include room temperature operation, compact size, and potential for optical control, among others. To be useful for practically relevant applications, output power levels of at least 1 mW at 300 GHz and 20  $\mu$ W at 1 THz are desirable [4], but these are yet to be demonstrated in RTD technology.

This paper provides a review of mm-wave RTD electronic oscillators developed in our group together with a description of the first wireless transmission experiments with these. An RTD with a light absorption layer, the RTD photo-detector (RTD-PD), shows great potential applications for optical-electrical modulation and photo-detection [3]. This device can benefit from the RTDs capability of high frequency operation, and so millimeter-wave (mm-wave) RTD-PD oscillators have been realised and are also reported here.

## II. MM-WAVE RTD OSCILLATORS

We have previously reported mm-wave oscillators with oscillations frequencies up to 300 GHz [2]. They employ the

typical double barrier quantum well (DBQW) RTD structure. It consists of a 5.5 nm  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  quantum well sandwiched between 1.4 nm AlAs double barriers. The collector and emitter layers are each 80nm thick  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  highly doped ( $2 \times 10^{18} \text{cm}^{-3}$ ) with Si. The fabricated device sizes of this InGaAs/AlAs RTD were  $3 \times 5$ ,  $4 \times 4$  and  $5 \times 5 \mu\text{m}^2$ . They showed a peak voltage of 1 V, a valley voltage of 1.6 V, peak current density of about  $2.2 \text{mA}/\mu\text{m}^2$ , and a peak to valley current ratio (PVCR) of about 3.1.

The oscillator circuit and its RF equivalent circuit are shown in Fig. 1. Details of the design and realisation are described in Ref.[5]. A 125 GHz oscillator provided 0.68 mW output power while the 156 GHz and 308 GHz oscillators gave 0.47 mW and 0.33 mW output power, respectively. The measurement results are summarized in Table 1. The spectrum of the 308 GHz oscillator is shown in Fig. 2. Even though the output power levels are reasonable, the DC to RF conversion efficiencies is low, under 0.5%.

Utilizing a 300GHz RTD oscillator, first experiments on wireless transmission with these devices are underway. The basic measurement setup is as shown in Fig. 3. PRBS data was applied through a bias-T to the RTD oscillator. The receiver was comprised a 300GHz horn antenna, Schottky barrier diode (SBD) detector, low noise amplifier (LNA) and an oscilloscope. The separation between the antennas was 5 cm. The measured eye diagrams at data rates of 2 Gbps and 7 Gbps are shown in Fig. 4. The measurement setup is being now optimized for clearer eye diagrams and higher transmission rates.

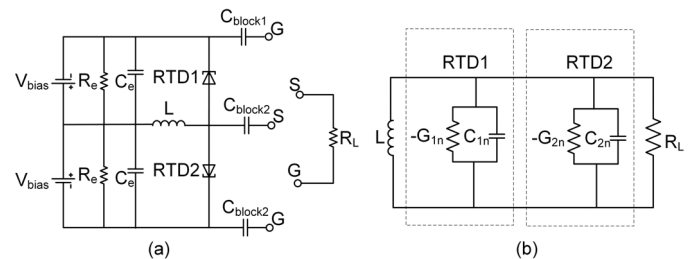


Fig. 1. (a) Two RTD oscillator schematic circuit. Each RTD is biased individually with its own DC stabilization circuit  $R_e$  and  $C_e$ . (b) Oscillator RF equivalent circuit excluding device parasitic elements  $G_n$  and  $C_n$  are the device

conductances and self-capacitances in the NDC region, respectively, and  $R_L$  is the load resistance, which is  $50\Omega$  in our case.

TABLE I. SUMMARY OF RTD OSCILLATORS RESULTS

Device size ( $\mu\text{m}^2$ )	CPW $Z_0(\Omega)$ /length ( $\mu\text{m}$ )	Freq. (GHz)	Power (dBm/mW)	DC Power (mW)
5×5	50/30	125	-1.7/0.68	415
3×5	50/30	156	-3.3/0.47	374
4×4	25/10	308	-4.8/0.33	191

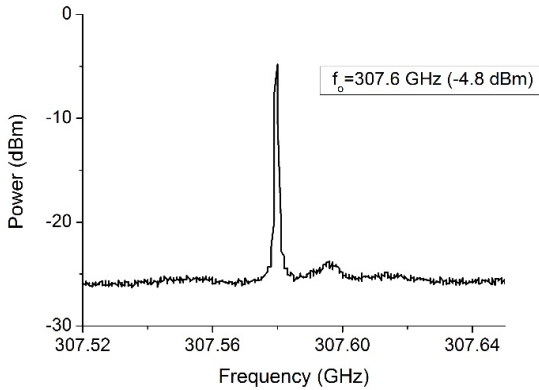


Fig. 2. Measured spectrum of the 307.8 GHz oscillator when  $V_{\text{bias}}=1.65$  V,  $I_{\text{bias}}=116$  mA.

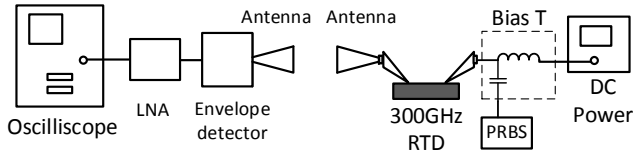


Fig. 3. Schematic wireless communication measurement setup by using 300GHz RTD oscillator.

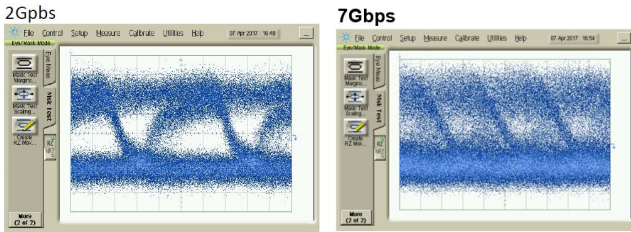


Fig. 4. Measured eye diagrams at 2 Gbps and 7 Gbps from a 300GHz carrier frequency.

### III. RTD-PD DEVICES AND OSCILLATORS

As RTD devices exhibit negative differential conductance (NDC) gain over a wide bandwidth, the RTD-PD device would act as optical receiver with a build in amplifier, and which can convert a modulated optical signal into the wireless domain [6,7]. Different from RTD device layer structure, the RTD-PD structure includes a photo-absorption layer as shown in Table II. Here, the InGaAs/AIAs RTD was integrated with 500 nm

photo absorption InGaAs layer on top of DBQW to form the RTD-PD.

#### A. DC characteristics

Results of  $10 \times 10 \mu\text{m}^2$  sized RTD-PDs are presented here. The central optical window on top of the collector mesa is as shown in Fig. 5. The device optical window size is about  $3 \times 8 \mu\text{m}^2$ . The I-V characteristics under dark and light illumination are compared in Fig. 6. Under dark condition, the device shows negative differential conductance (NDC) region between 1.1 – 1.4V. The peak current density was about  $0.3 \text{ mA}/\mu\text{m}^2$ , peak to valley current ratio (PVCR) about 1.5. The device stationary optical response was investigated with non-modulated continuous wave (CW) laser at 1310 nm and 1550 nm. This measurement work was done at Universidade do Algarve. The measurement setup is shown in the inset of Fig. 6. The RTD-PD was biased from left (probe). The cleaved single mode optical fiber was aligned with the optical window from device top mesa. The light with wavelength 1310 nm and 1550 nm was coupled into the RTD-PD with 0.1mW and 1 mW power. As shown in Fig. 6(a), the optical DC response of 1310 nm laser with different optical power are compared with dark current. The maximum response was about 5 A/W when RTD-PD was biased close to the peak voltage. The injected laser power was 1 mW. As shown in Fig. 6(b), the maximum responsivity of 1550 nm (1 mW) was about 2 A/W. The main difference is due to high absorption efficiency at 1310nm wavelength.

TABLE II. RTD-PD EPITAXIAL LAYER STRUCTURE

Layer #	Thickness ( $\text{\AA}$ )	Composition	Doping ( $\text{cm}^{-3}$ )	Description
12	450	InGaAs	$3\text{E}19$ : Si	Collector
11	800	InGaAs	$3\text{E}18$ : Si	Collector
10	5000	InGaAs	$5\text{E}16$ : Si	Absorption
9	20	InGaAs	Un-doped	Spacer
8	17	AlAs	Un-doped	Barrier
7	47	InGaAs	Un-doped	Well
6	17	AlAs	Un-doped	Barrier
5	20	InGaAs	InGaAs	Spacer
4	200	InGaAs	$2\text{E}16$ : Si	Spacer
3	80	InAlAs	$3\text{E}18$ : Si	Emitter
2	4000	InGaAs	$3\text{E}19$ : Si	Emitter
1	200	InP	Un-doped	Buffer
Substrate SI : InP				

#### B. RTD-PD oscillators

The circuit topology for the RTD-PD or optoelectronic oscillator is the same as that for an electronic RTD oscillator presented in section II. Two RTD-PD devices are integrated in the circuit. The stabilizing resistor  $R_c=20 \Omega$ , MIM capacitor  $C_c=60 \text{ pF}$  and DC blocking capacitor  $C_b=7 \text{ pF}$ . A micrograph of the fabricated RTD-PD oscillator is shown in Fig.7. The oscillators were characterized on-wafer by using Agilent E4448A spectrum analyzer. A Cascade ACP65 RF probe was used to probe the output of these oscillators. The actual measurement system loss was characterized by calibrated another signal source Wiltron 68187B. The results are

summarized in Table III. It shows that Q-band RTD-PD oscillators with over 1 mW output power have been developed. The highest measured RTD-PD oscillator frequency was 102.8 GHz. The frequency can be further increased by optimizing the device and CPW design.

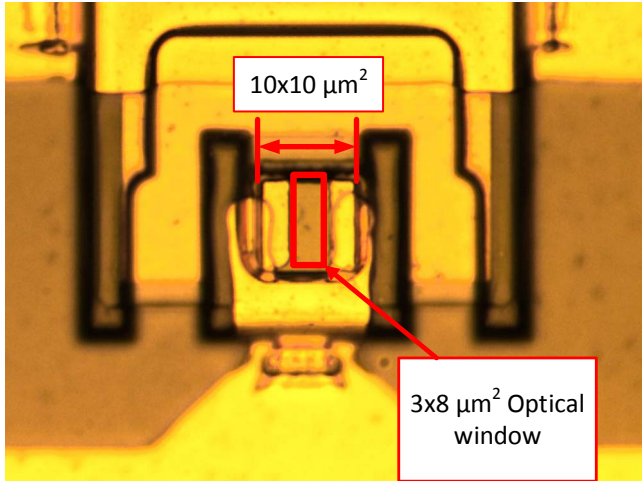


Fig. 5. The micrograph of the top-view of the fabricated device. The device size was  $10 \times 10 \mu\text{m}^2$ , the optical window size was  $3 \times 8 \mu\text{m}^2$ .

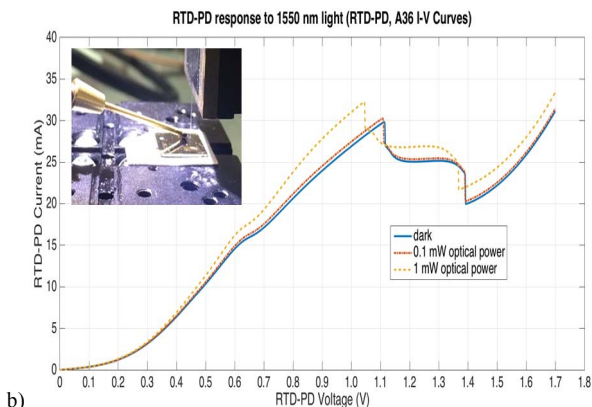
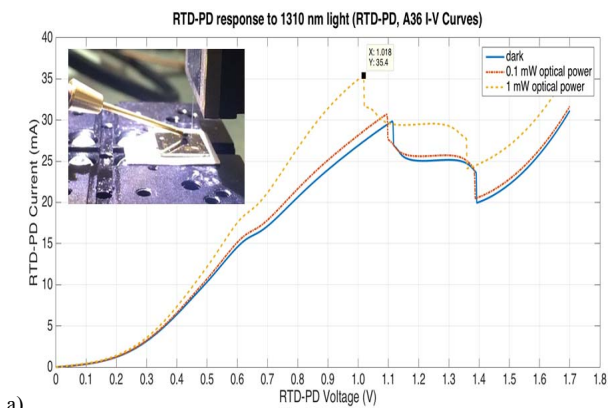


Fig. 6. RTD-PD stationary optical response with light injection power of 0.1 mW and 1 mW (a) The optical response of 1310 nm wavelength. (b) The optical response of 1550 nm wavelength. The device shows large responsivity of 5 A/W for 1310 nm compared to 1550 nm due to high absorption efficiency. Inset shows the measurement setup. The device was biased from left (probe). The injected light was coupled from the top side.

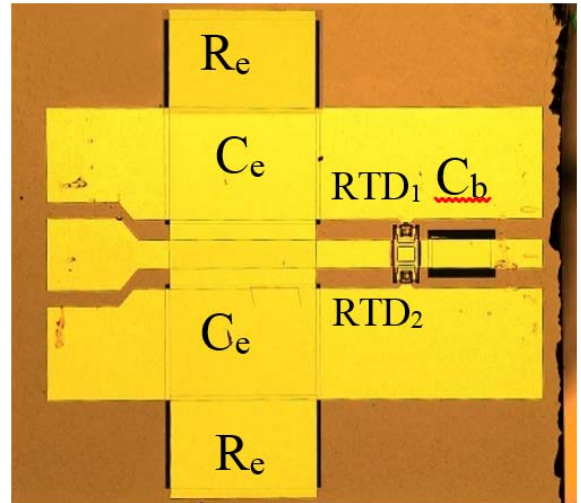


Fig. 7. Fabricated RTD-PD oscillator,  $R_e=20 \Omega$ ,  $C_e=60 \text{ pF}$ ,  $C_b=7 \text{ pF}$ .

TABLE III. RTD-PD OSCILLATOR MEASUREMENT RESULTS.

Device size ( $\mu\text{m}^2$ )	Optical window ( $\mu\text{m}^2$ )	CPW length ( $\mu\text{m}$ )	Measured Freq(GHz)	Measured Power (dBm)
100	24	260	34.4	0.4
100	24	260	37.0	0.1
225	50	75	44.4	+1.4
100	24	25	102.8	-15

#### IV. DISCUSSION AND CONCLUSION

The results presented in the paper show great potential to utilize RTD/RTD-PD as high speed optical/electrical modulated RF transmitter. 300 GHz RTDs in wireless transmission experiments supported data rates up to 7Gbps (requiring error correction). By optimizing the circuit design and measurement setup, over 10 Gbps can be expected [8]. The RTD-PD approach provides a high efficiency, low cost solution for seamless integration of high speed fiber network with THz wireless communication. Further work to increase the oscillator power and efficiency, and on wireless and optical-wireless data transmission is currently under investigation.

#### ACKNOWLEDGMENT

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