Mm-wave/THz Multi-Gigabit Wireless Links

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***Abstract* — This paper presents millimetre-wave (nm-wave) and terahertz (THz) multi-gigabit wireless links which use planar integrated circuit high power resonant tunnelling diode (RTD) oscillators as transmitters. By employing appropriate circuitry and improved device epilayer design, the oscillators generate an output power of 2 mW at 84 GHz and 1 mW at 206 GHz, respectively, which are the highest reported output powers for RTD-based oscillators at the respective frequencies. Preliminary wireless communication results show 15 Gbps and 13 Gbps data rates over distances of about half a meter.**

***Keywords* — Resonant tunneling diode (RTD), oscillator, THz sources, wireless communication**

I. INTRODUCTION

There is great demand for ultra-high speed wireless communication especially with the development of modern multimedia technology. The typical application scenarios include wireless local area networks (WLAN), wireless connection in data centres, chip to chip interconnects, and wireless backhauling [1]. Currently, high-resolution videos account for about 69% of all data viewed on mobile devices and are expected to reach 79% by 2020. At this pace, short-range wireless communication will soon require data transfer speeds of tens of gigabits per second (Gbps), which current wireless technology cannot support due to the fundamental limitation of the narrow bandwidth available at the low microwave frequencies used today. Instead of the great effort being devoted to improve spectral efficiency by using advanced modulation schemes and signal processing techniques, the other approach is to move to unregulated spectrum in millimetre-wave (mm-wave) or terahertz (THz) frequency range for higher bandwidth [2]. The second approach is presented in this paper by using a resonant tunnelling diode (RTD) as a transmitter.

Compared to any other traditional electronic devices such as transistors, the RTD is the fastest solid-state device with a fundamental frequency of oscillations of around 2 THz recently demonstrated [3]. Room temperate operation, compact device size, low circuit complexity, low design and energy cost, all makes the RTD a very promising candidate for THz applications. The main limitation for the RTD is also the same for any other solid-state THz sources; the low output power. We are developing an integrated circuit RTD technology which aims to improve the output power level by using optimised epitaxial designs and/or circuit-based power combining techniques. Using this approach, 2 mW at 84 GHz and 1 mW at 206 GHz RTD transmitter have been developed, and these have been used in preliminary experiments to demonstrate over 10 Gbps wireless links of around 0.5 m.

The paper is organized as follows. Section II describes the RTD devices including epilayer design and their current-voltage (*I-V*) characteristics. Section III introduces the RTD transmitter design and its characterization, while Section IV describes the wireless communication measurements and results. Section IV provides conclusions of the work.

II. RTD DEVICES

The core of an RTD device comprises a double barrier quantum well (DBQW) epitaxial layer structure which consists of a narrow band gap (E_g) epilayer sandwiched between two thin wide bandgap epilayers. This is shown in Fig. 1 and consists of an InGaAs layer with bandgap $E_g = 0.71$ eV located between two AlAs barriers with $E_g = 2.16$ eV. Under bias voltage, electrons can tunnel through these barriers despite having lower self-energy [4]. The *I-V* characteristic of an RTD device exhibits a negative differential resistance (NDR), which is the basis of RTD oscillators. The inset of Fig. 1 is a micrograph of the fabricated device.

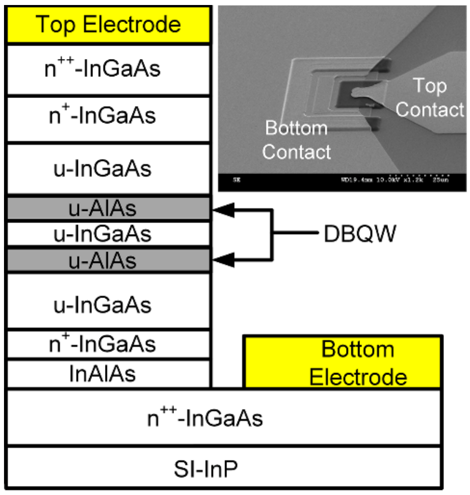


Fig. 1. Schematic layer structure of the RTD. The inset SEM picture shows the fabricated 16 μm^2 (top mesa) sized device.

The fabrication process uses only optical lithography. The device mesa is defined by wet etching and passivated by polyimide. More fabrication details can be found in [5]. The *I-V* characteristics of the device are shown in Fig. 2. The *I-V* characteristic was modeled by using a 9th order polynomial which shows a good fit with measurements. It was also modelled with a quasi-physical model in which numerical constants were determined empirically [6]. The differential conductance (G_n) was derived from the modelled *I-V* and is also shown in Fig. 2. The NDR region is between peak voltage $V_p = 0.9$ V and valley voltage V_v = 1.7 V, with a minimum value of G_n of -42.5 mS. The peak current density is 187 kA/cm^2 and the peak to valley current ratio (PVCR) being about 2.5. The maximum available power (P_{max}) of single RTD oscillator can be estimated from (1) to be around 2.5 mW, where ΔV = 0.8 V and ΔI = 16.6 mA are the peak-to-valley voltage and current differences, respectively [7].

$$P_{max} = \frac{3}{16}\Delta V \Delta I \qquad (1)$$

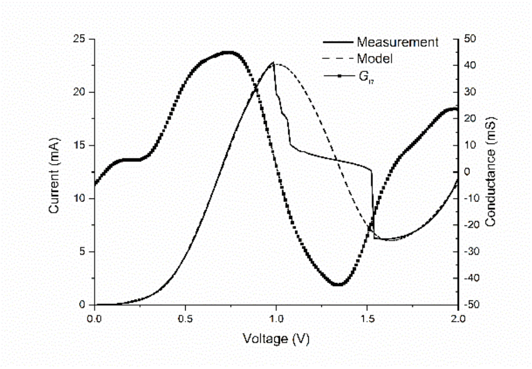


Fig. 2. Measured and modeled *I-V* characteristics for a 16 μm^2 RTD. The negative differential conductance G_n is also shown. Note that the G_n is negative across the entire NDR region with a minimum value of -42.5 mS.

III. RTD OSCILLATOR DESIGN AND MEASUREMENT

The high power RTD oscillator design proposed here employs two RTDs in parallel, with each device biased individually. The schematic circuit diagram of the oscillator is shown in Fig. 3 (a), where R_e is the stabilizing resistor to suppress the low frequency bias oscillations. The bypass capacitor C_e is used to decouple the DC and RF sections of the circuit. Inductor L is designed to resonate with the RTDs' self-capacitance in order to determine the oscillating frequency. R_L is the load resistance and set to 50 Ω to match the system impedance in the typical characterization environment. As the two RTD devices are nominally identical, and are biased simultaneously, they work as an equivalent large single NDR device with double negative differential conductance and capacitance. Fig. 3 (b) shows the RF equivalent circuit, where RTD_1 and RTD_2 are assumed identical. Each RTD is modelled as an RC model comprising the contact resistance R_s, self-capacitance C_n, and the negative conductance G_n. As the two RTDs are in parallel, the total capacitance $C_n^* = 2C_n$, negative conductance $G_n^* = -2G_n$, and series resistance $R_s^* = R_s/2$.

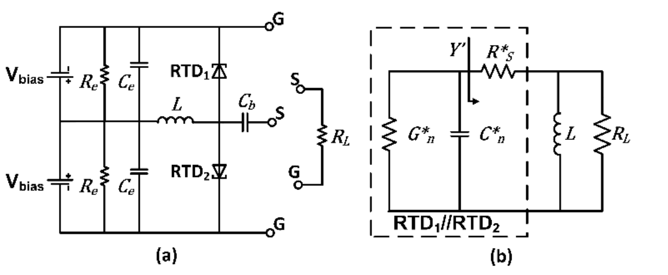


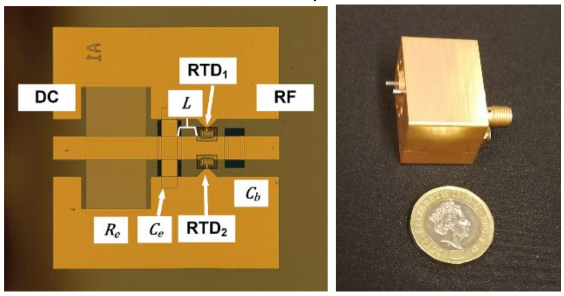
Fig. 3. (a) Schematic circuit of an oscillator employing two RTDs, each with its own DC stabilization circuit R_e and C_e. (b) Oscillator RF equivalent circuit.

The oscillator frequency f_o is determined from

$$imag[Y'] + \omega_0 C_n^* = 0 \qquad (2)$$

where Y' is the admittance of the indicated circuit, and is given by:

$$f_o = \frac{1}{2\pi L(G_L R_s + 1)}\sqrt{\frac{L}{C_n} - R_s^2} \qquad (3)$$



(a) (b)

Fig. 4. (a) Fabricated double RTD oscillator. 2RTDs are connected in parallel. Each device is biased individually with resistor R_e and bypass capacitor C_e. C_b is the DC block capacitor. The CPW length l depends on the designed frequency. (b) Packaged W-band RTD transmitter.

A micrograph of the fabricated circuit is shown in Fig. 4. R_e was realized as a thin film NiCr resistor. The decoupling capacitor C_e and DC block capacitor C_b was fabricated by using metal-insulator-metal (MIM) capacitor. The inductor L is realised by a coplanar waveguide (CPW) transmission line with length of l terminated by C_e, which acts as a short-circuit.

The oscillators were measured on-wafer. The measurement results are summarized in Table I. It is worth to note that the output powers are reported here directly from RTD oscillators without any power amplifier stage. Also note that while the 2 mW 84 GHz oscillator employed the 2-RTD device circuit topology described above, the 1 mW 260 GHz oscillator employed only a single RTD device [9].

TABLE I: SUMMARY OF RTD OSCILLATORS PERFOMANCE

Device size (µm^2)	Fundamental Freq. (GHz)	Power (dBm)	DC Power (mW)
5x5	60	**5**	120
5×5	84	**2.8**	114
4×4	260	**0**	180
4×4	308	-4.8	191

IV. MULTI-GIGABIT WIRELESS LINK

The block diagram of the wireless system architecture is illustrated in Fig. 5.

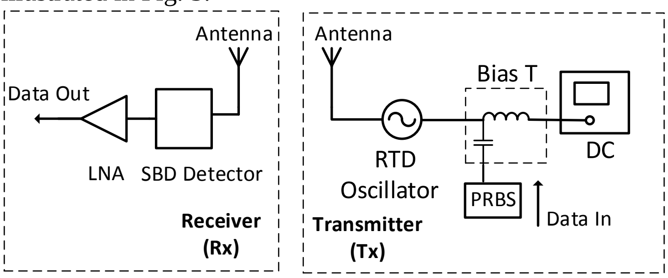


Fig. 5. Block diagram of the wireless system architecture.

The transmitter (Tx) consists of a voltage controlled RTD oscillator (RTD-VCO) with an antenna. No power amplifier (PA) is employed at this stage which shows the simplicity/merit of RTD transmitter. The data is superimposed over DC bias through a bias tee. On the receiver (Rx) side, the received signal and demodulated by a Schottky barrier diode (SBD) envelope detector and then the baseband data is amplified by a low noise amplifier (LNA) and displayed on oscilloscope.

As depicted in Fig. 6, both ASK and OOK modulation schemes are applicable depending on the bias position and amplitude of the data. For ASK, the device is biased in the NDR region with data amplitude within NDR, and for OOK the device is biased near the peak voltage. However, in our experiment, ASK demonstrated better results with low BER and the results are reported in this paper.

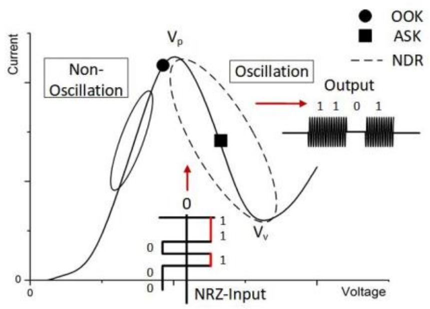


Fig. 6. Typical RTD device *I-V* characteristics and illustration of ASK /OOK modulation.

The lab measurement setup is shown in Fig. 7. The 2^{15}-1 PRBS (pseudo-random binary sequence) from Keysight M8040A provided the data. The horn antennas had a gain of 21 dBi. The zero bias Schottky barrier diode (SBD) had a typical responsivity of 2V/mW, specified by the manufacturer. The LNA had 20 GHz bandwidth and 12 dB gain. A Keysight Technologies 86100C oscilloscope was used to display eye diagrams, see Fig. 8 and 9. The J-band wireless link was also characterized in a similar manner. The antenna and detector were replaced with higher bandwidth J-band components. The results are summarized in Table II. A high data rate of 15 Gbps using the 84 GHz carrier [8] and 13 Gbps using the 260 GHz carrier [9] were achievable, both with correctable error rates.

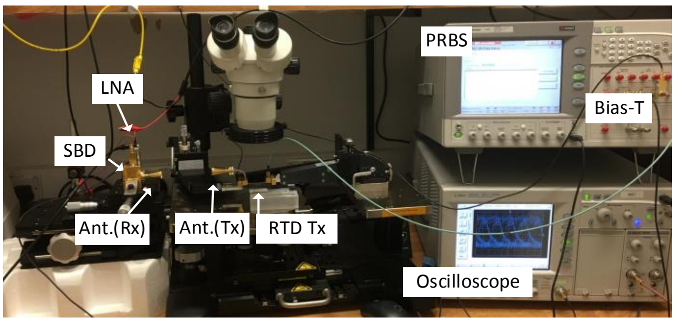


Fig. 7. W-band wireless communication measurement setup in the lab.

Table II: Wireless communication perfomance

	(1)	(2)
Frequency	84 GHz	206GHz
Power consumption	118 mW	180 mW
Antenna/gain	Horn/21dBi	Horn/21dBi
Distance	50 cm	20cm
Maximum Data Rate	15 Gbps	13 Gbps
BER	1.0E-6@5Gbps 3.6E-4@10Gbps 4.1E-3@15Gbps	N/A
Modulation	ASK	ASK

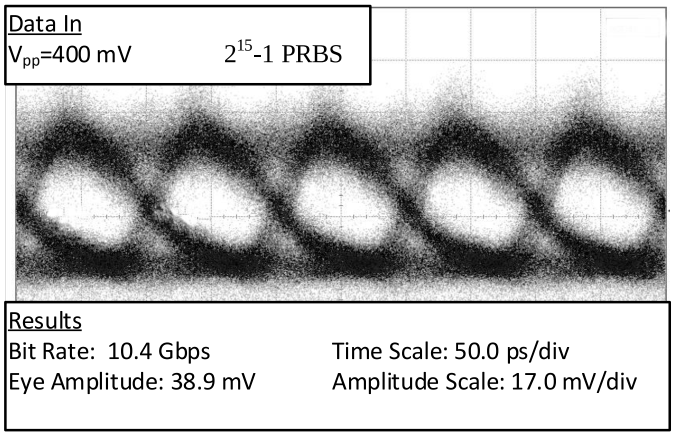


Fig. 8. 10 Gbps ASK eye diagram: when RTD is based at 1.2 V with data amplitude 400 mV using the 84 GHz transmitter

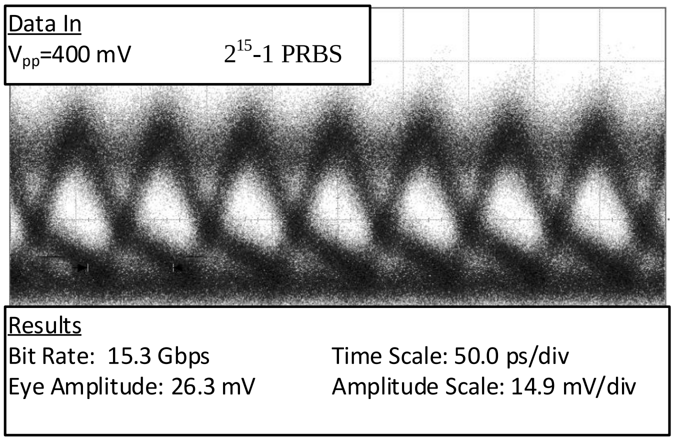


Fig. 9. 15 Gbps ASK eye diagram: when RTD is based at 1.2 V with data amplitude 400 mV using the 84 GHz transmitter.

V. Discussion and Conclusion

The work reported here demonstrates the potential of RTD oscillators for applications as compact sources for multi-gigabit wireless communication systems. The RTD transmitters provide a very promising simple, low cost, compact solution for future ultra-fast wireless communication systems. Future work is focused on RTD epitaxial layer design to increase the oscillator output power at THz frequencies, the development of integrated modulators and RTD based receivers for numerous applications.

ACKNOWLEDGMENT

The authors thank the staff of the James Watt Nanofabrication Centre (JWNC) at the University of Glasgow for help in fabricating the devices.

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