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THz Electronics for Data Centre Wireless Links - the TERAPOD Project

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Abstract—**This paper presents an overview of the terahertz (THz) resonant tunneling diode (RTD) technology that will be used as one of the approaches towards wireless data centres as envisioned on the EU H2020 TERAPOD project. We show an example 480 µm × 680 µm THz source chip at 300 GHz employing a 4 µm × 4 µm RTD device with 0.15 mW output power. We also show a basic laboratory wireless setup with this device in which up to 2.5 Gbps (limited by equipment) was demonstrated.**

***Keywords*—monolithic microwave integrated circuit (MMIC); resonant tunneling diode (RTD); oscillator; THz sources.**

I. INTRODUCTION

WITH the exponentially increasing data traffic, especially those on wireless channels, the data rate for wireless communication is expected to reach 100 Gbps to meet the market requirements within 10 years [1], which leads to the demand for larger bandwidth available. As a result, carrier frequencies have been increasing to meet the bandwidth requirements, ranging from millimetre-waves [2] to the terahertz (THz) band [3]. In the so-called THz gap, approx. 0.3 to 3 THz, both photonics based and electronics based solutions are under development [3], [4]. Many THz (gap) electronic sources today are based on low frequency sources with multiplier chains to achieve the THz signal [5]. The efficiency of this architecture is low and the sources are not compact. Therefore, a number of electronic devices including Gunn diodes, IMPATT diodes, resonant tunnelling diodes (RTDs), etc have been considered for use as THz sources. Of these, the InP-based resonant tunnelling diode (RTD) is the fastest electronic device and, indeed, a number of demonstrations of this large RTD bandwidth have been reported recently [6]. Demonstrations of wireless transmission using RTD oscillators at 300 GHz [7] and 500 GHz [8] have been reported. Individual RTD oscillators, however, exhibit low output power in the micro-Watt range, while high power in the milli-Watt range is desirable. This, together with high gain antennas, would mitigate against the higher free space loss at THz frequencies and so enable practical communication links over 10's -100's of metres [9].

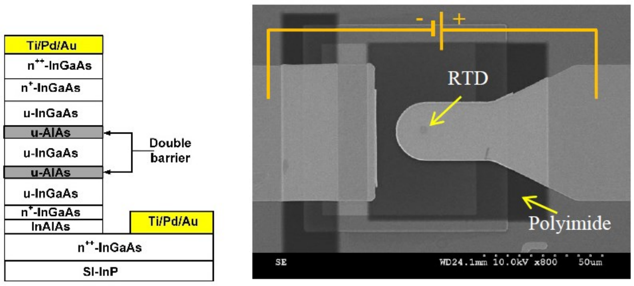
On TERAPOD, the development of THz wireless communications technology is seen as a market game changer in the modern data centre industry as it has the potential to significantly impact some of the current challenges experienced by all data centre operators, managing data traffic hotspots, cabling complexity that leads to increased service operation costs and cabling density that reduces cooling efficiency. To this end, THz wireless links enabled by RTD technology would replace the copper cables. This will require the realisation of higher output power of RTD oscillators, a challenge which we have been tackling over the past years [10]-[12]. We have, for instance, developed designs that employ the largest possible devices and also developed an oscillator circuit topology that employs two RTD devices. Using this approach, 76 GHz InP-based RTD oscillators with around 1 mW were realized [10]. Thereafter, D-band oscillators operating at 125 GHz, 156 GHz and 166 GHz, with output power of 0.34 mW, 0.24 mW, 0.17 mW, respectively, were also demonstrated [11]. These oscillators used a shorted coplanar waveguide (CPW) lines of characteristic impedance (Z_0) of 50 Ω to realize the inductances required to resonate with the device self-capacitance for a given target oscillation frequency. At very high frequencies, J-band, the length of the shorted CPW line becomes extremely short, and so an alternative low Z_0 shorted microstrip line using polyimide as the dielectric layer has been developed [12].

In this paper, the basic RTD source technology will be reviewed using the example of a J-band oscillator. We will also report on the use of this oscillator in wireless communications experiments with high data rates of up to 2.5 Gbps and a range of 5 cm.

II. RTD TECHNOLOGY

The layer structure of the RTD wafer which was used in the oscillator reported here was grown by molecular beam epitaxy (MBE) by IQE Ltd on a semi-insulating InP substrate. It employs a 4.5 nm $In_{0.53}Ga_{0.47}As$ quantum well, 1.4 nm AlAs barriers and 25 nm spacers, and is illustrated in Figure 1(a) where the emitter, collector and contact layers are also shown. This double barrier quantum well (DBQW) design offers a current density J_P of ~3 mA/µm^2 and a PVCR of 3.5. The collector and emitter layers are made of highly Si doped $In_{0.53}Ga_{0.47}As$ material (3×10^{19} cm^{-3}). The RTD devices were fabricated using photolithography. The fabricated RTD has a mesa size of 4 µm × 4 µm. Chemical wet etching (H_3PO_4:H_2O_2:H_2O=1:1:38) was used to define the RTD mesa.

This recipe has an etching rate of around 100nm/min. Polyimide PI-2545 was used for device passivation. A scanning electron microscope (SEM) picture of a fabricated RTD device is shown in Figure 1(b). The 4 µm × 4 µm RTD devices exhibit a peak-valley bias voltage difference (ΔV) of around 0.6 V and peak-valley current difference (ΔI) of around 25 mA. Epitaxial design for a large negative differential resistance (NDR) region, i.e. large ΔV and ΔI, is key to high oscillator power, and new approaches to achieve this will be adopted on TERAPOD.

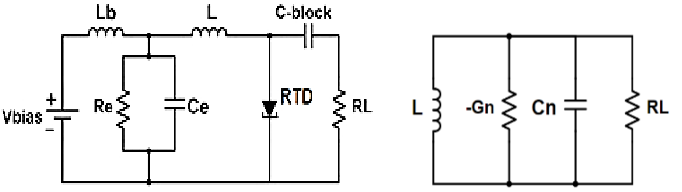


(a) (b)

Fig. 1. (a) The schematic epitaxial layer structure of an RTD device. (b) SEM of a fabricated RTD device.

III. RTD OSCILLATOR DESIGN & REALISATION

The RTD oscillator design approach presented here employs a single RTD device as shown in Figure 2(a). The shunt resistor R_e is used to suppress the low frequency bias oscillations and the bypass capacitor C_e is used to ground the RF signal. Inductance L is designed to resonate with the RTD self-capacitance to obtain the desired frequency. L_b is the biasing cable inductance. R_L is the load resistance. The small signal equivalent circuit of the oscillator circuit of Figure 2(a) is shown in Figure 2(b). The RTD is modelled by its lumped equivalent circuit model, a negative differential conductance $-G_n$ in parallel with the self-capacitance C_n.



(a) (b)

Fig. 2. (a) The RTD oscillator schematic circuit. (b) RTD oscillator RF equivalent circuit excluding parasitic elements.

The circuit topology was realized in MMIC form as shown in Figure 3. A thin film NiCr resistor was used to realise R_e, while a metal-insulator- metal (MIM) capacitor to realise C_e. Thin dielectric layer Si_3N_4 (75 nm) was deposited by inductively coupled plasma (ICP) chemical vapour deposition (CVD). The inductance L was realized by a microstrip transmission line short stub. It consisted of a 20 µm wide signal line on top of a 1.2 µm thick polyimide. With this configuration, the characteristic impedance of the microstrip line is 10.4 Ω. The short-circuit termination was provided by capacitor C_e. R_L was introduced by the input impedance of the spectrum analyser or power meter which is usually 50Ω.

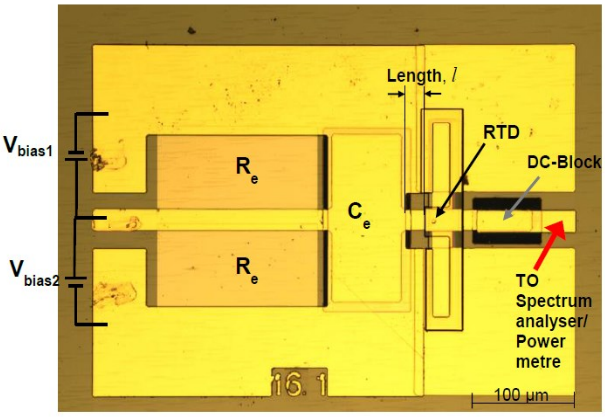
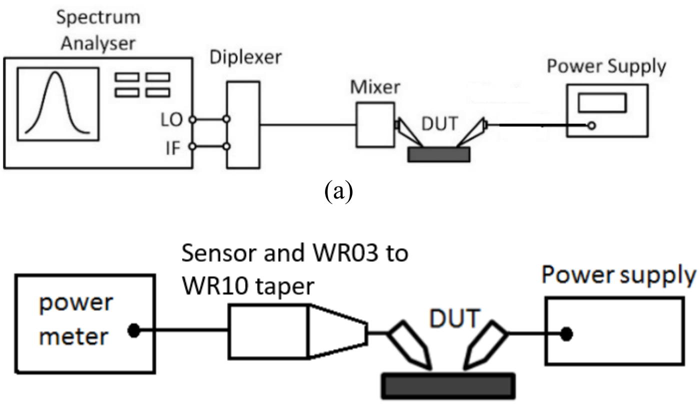


Fig. 3. Micrograph of a fabricated RTD oscillator circuit.

IV. RTD OSCILLATOR MEASUREMENT

A. Measurement Setup

The oscillator was measured on-wafer using Agilent's E4448A spectrum analyser. At the DC port, the oscillator was biased using a GSG Cascade probe. At the RF port, a WR-03 GSG Picoprobe was used to measure the output signal of the oscillator. The schematic diagram of the measurement setup is shown in Figure 4 (a).



(a)

(b)

Fig. 4. Schematic diagram (a) on-wafer spectrum measurement, (b) Power measurement setup for J-band frequencies.

The signal was mixed down using a J-band harmonic mixer from Farran Technology (WHMB-03). The spectrum analyser and mixer were connected through a diplexer which is used to separate the local oscillator (LO) and intermediate frequencies (IF). With built in signal identification function of spectrum analyser, the oscillation frequency was accurately identified.

As the conversion loss of the mixer is not accurately specified by the manufacturer, the actual output power was measured by the Erikson PM5 power meter. Since the input of the power sensor head is WR-10 (W-band) waveguide, A WR-03 to WR-10 tapered waveguide was used as shown in Figure 4 (b).

B. Measurement Results

Oscillators, each employing a single 4 µm × 4 µm RTD devices, with shorted microstrip lengths of 88 µm and $Z_0 = 10.4\ \Omega$ were fabricated and measured. The measured oscillation frequency was 312 GHz and output power was 0.15mW. The measured spectrum is shown in Figure 5.

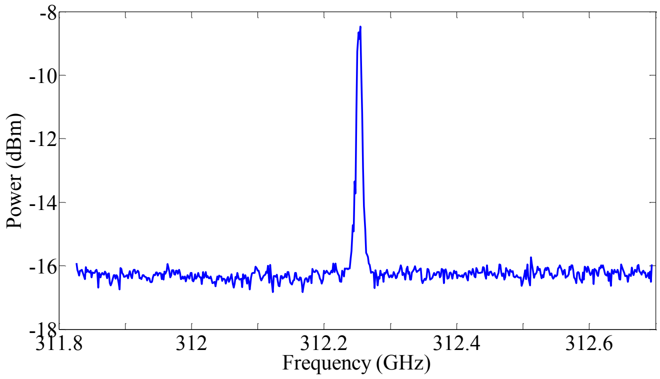


Fig. 5. Measured spectrum of the 312 GHz RTD oscillator.

V. WIRELESS EXPERIMENTALSETUP

A schematic of the wireless experimental setup is illustrated in Figure 7(a). A pseudorandom binary sequence (PRBS) data generator (Anritsu MP1763C) is used and is clocked using an external signal generator. A Bias-T connected to a 67 GHz probe is used to relay both the DC bias and the data from the PRBS to the DC port of the oscillator. The oscillator output (RF port) is connected via a GSG probe (including waveguide transition) to a 300 GHz horn antenna to transmit the output signal (carrier + data) which is then received by another 300 GHz horn antenna that is connected to a Schottky barrier diode (SBD) detector, the WR3.4ZBD from VDI. The SBD is connected to a low noise amplifier from VDI which feeds the data into a real time oscilloscope (Rohde & Schwarz RTO1024). The oscilloscope uses the same clock that is used to clock the PRBS and data from the SBD to generate the eye diagrams. Figure 7(b) is a picture of the measurement setup.

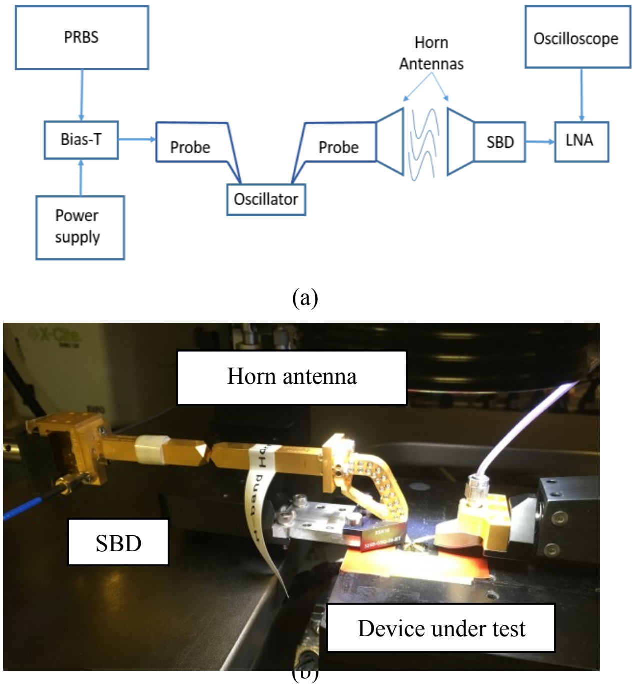


Fig. 7. (a) 300 GHz wireless measurement setup, (b) Picture of a device under test with an SBD and horn antennas.

In the experiment, the RTD was biased at 1.83 V and was drawing a current of 200 mA. A 600 mVp-p data signal was applied from the PRBS into the Bias-T. Clear eye diagrams were observed on the oscilloscope. The data rates were increased from 500 Mbps up to 2.5 Gbps (limit for our real time oscilloscope) and the result is shown in Figure 8.

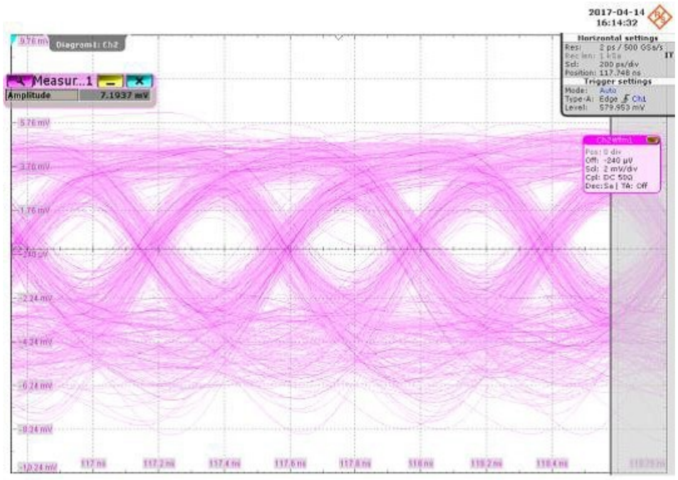
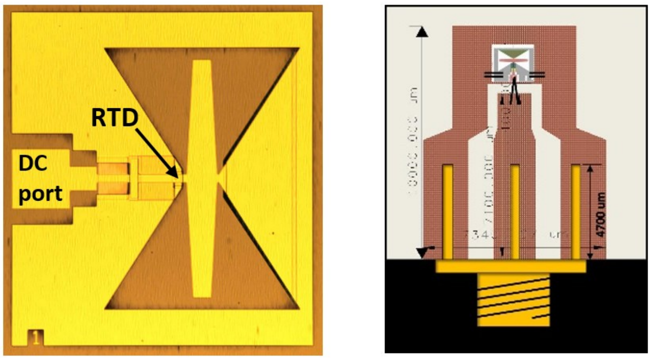


Fig. 8. Eye diagrams of 2.5 Gbps wireless data rates transmitted over a 300 GHz carrier signal.

For future work, TERAPOD project aims to demonstrate RTD oscillators with around 2mW of output power at 300 GHz and have these packaged and integrated with suitable antennas for use in wireless data centre links with data rates of at least 10 Gbps. 300 GHz oscillators with an integrated slot bow-tie antennas have been designed and realised. A micrograph of one such is shown in Figure 9(a). In Figure 9(b), an illustration of the oscillator mounted on a PCB is shown for a compact transmitter requiring just bias and data (on the bias line) to work.



(a) (b)

Fig. 9. (a) Micrograph of 300GHz oscillator with an integrated slot-bowtie antenna, (b) Layout of wire bonded oscillator to a PCB with SMA connector.

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