15 Gbps Wireless Link Using W-band Resonant Tunnelling Diode Transmitter

Jue Wang[1], Abdullah Al-Khalidi[1], Razvan Morariu[1], Afesomeh Ofiare[1], Liquan Wang[2] and Edward Wasige[1]

[1] High Frequency Electronics Group, School of Engineering, University of Glasgow, UK

[2] Shanghai Electro-Mechanical Engineering Institute, China

jue.wang@ glasgow.ac.uk

Abstract **—A 15 Gbps wireless link over 50 cm distance is reported in this paper. A high power and low phase noise resonant tunneling diode (RTD) oscillator is employed as the transmitter. The fundamental carrier frequency is 84 GHz and the maximum output power is 2 mW without any power amplifier. The measured phase noise value was -79 dBc/Hz at 100 KHz and -96 dBc/Hz at 1 MHz offset. The modulation scheme used was amplitude shift keying (ASK). The 15 Gbps data link showed a correctable bit error rate (BER) of 4.1×10^{-3}, while lower data rates of 10 Gbps and 5 Gbps had BER of 3.6×10^{-4} and 1.0×10^{-6}, respectively.**

Keywords **—resonant tunneling diode, wireless communication, amplitude shift keying (ASK).**

I. Introduction

There is great demand for ultrafast wireless communication systems. By the extrapolation of Edhom's law, it is expected that 100 Gbps data rates will be required in the very near future [1]. The applications include wireless personal area networks (WPAN), kiosk downloading where high bandwidth is required for multimedia streaming, and machine to machine interconnects in places such as data centers where the cost and complexity of cabling can be significantly reduced.

For current wireless communication systems operating at carrier frequencies under 6 GHz, the great challenge to realizing high data rates is limited by the available narrow bandwidth, despite efforts to improve spectral efficiency by using advanced modulation schemes and signal processing techniques. To achieve the required performance for the mentioned above applications, multi-gigabit per second (Gbps) wireless links have been investigated outside of the present frameworks of standardization. Many candidate technologies operate in un-licensed bands and validate the technical feasibility for the future.

The resonant tunneling diode (RTD) is the fastest solid state device compared to any other traditional electronic devices such as Si MOSFET, heterojunction bipolar transistors (HBTs), high electron mobility transistors (HEMTs), impact ionization transit-time (IMPATT) diodes, and transferred-electron (Gunn) diodes. The fundamental frequency of an RTD oscillator is approaching 2 THz however the output power has been limited to μW range [2]. In this paper we propose a high power (2 mW) W-band RTD MMIC transmitter design. Using this, 15 Gbps over 50 cm wireless link has been demonstrated. The modulation scheme employed was amplitude shift keying (ASK), which has the advantages of simple implementation, low cost modulation/demodulation process and high bandwidth efficiency, etc. Compared with many standard CMOS techniques [3]–[5], the RTD transmitter design in the paper does not require any power amplifier (PA) or frequency multiplier/synthesizer stage, which greatly reduces the circuitry complexity and design costs. Besides low DC power consumption, the proposed transmitter is promising for future low-cost high speed wireless communication links.

The paper is organized as follows. Section II describes the transceiver architecture. Section III introduces the RTD transmitter design, including device technology, oscillator design and measurement results. Section IV describes the wireless measurement by implementing RTD transmitter. Section V provides conclusions of the work.

II. Transceiver architecture

A. Modulation scheme

The core layer structure of an RTD device consists of a narrow band gap (E_g) semiconductor material sandwiched between two thin wide band gap materials. Due to bandgap discontinuity, a double barrier quantum well (DBQW) structure is formed. As known from quantum mechanics, there are discrete resonant state energy levels at which electrons can tunnel through the barrier despite having lower self-energy, therefore the DC characteristics of an RTD device exhibits a negative differential resistance (NDR) as shown in Fig. 1. By using this NDR feature, high frequency RTD oscillators can be designed. The details are introduced in the next section. Both ASK and on-off keying (OOK) modulation are applicable to an RTD oscillator/transmitter depending on the bias position and the amplitude of input data as illustrated in Fig. 1. For OOK modulation, the RTD is biased near the peak voltage (V_p) position for input NRZ data to switch on-off the oscillator while for ASK modulation, RTD device is biased in the middle of NDR region. In our experiment, OOK shows poor performance than ASK, and so the OOK results will not be presented in this paper.

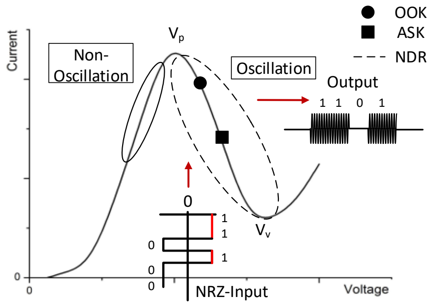


Fig. 1. Typical RTD device DC characteristics and ASK /OOK modulation diagram.

B. Transceiver architecture

The transceiver block diagram is illustrated in Fig. 2.

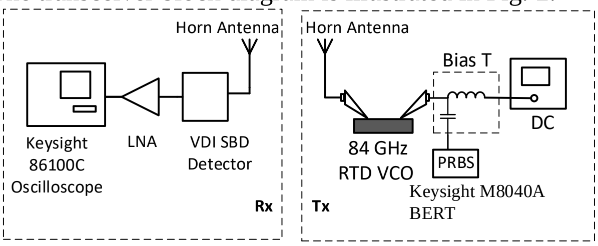


Fig. 2. Block diagram of the proposed transceiver.

The transmitter (Tx) consists of 84 GHz (fundamental) voltage controlled RTD oscillator (RTD-VCO) and WR-10 conical horn antennas. The data is superimposed over DC bias through a bias tee. As output power of RTD-VCO is high in mW range, no PA is employed in our experiment.

The receiver (Rx) consists of zero biased Schottky diode (SBD) envelope detector with a typical responsivity of 2V/mW and a low noise amplifier (LNA). The bandwidth of the LNA is 20 GHz bandwidth and 12 dB gain.

III. Transmitter Design

A. Resonant tunneling diode device

The RTD epitaxial layer structure for this work consists of a 4.5 nm InGaAs (indium gallium arsenide) quantum well sandwiched between double 1.4 nm AlAs (aluminium arsenide) barriers. A scanning electron microscope (SEM) micrograph of the completed RTD device is shown in Fig. 3. Fig. 3 (a) shows the fabricated single device with bonding pad for measurement. Fig. 3 (b) shows the 16 μm^2 central emitter mesa size. The fabrication process, involved for the presented devices is fully compatible with low cost optical lithography. The device I-V characteristic is shown in Fig. 4. Due to parasitic bias oscillation, the measured I-V is distorted, showing a plateau-like feature in NDR region. A polynomial numeric model was fitted to the data and shows good matching of the measurement, see Fig. 4. The peak current density was 150 kA/cm^2 and the peak to valley current ratio (PVCR) about 2.5. The calculated differential conductance (G_n) is shown by the red line. The NDR region is between peak voltage V_p = 0.9V and valley voltage V_v = 1.7V, with a minimum value of G_n of -42.5 mS.

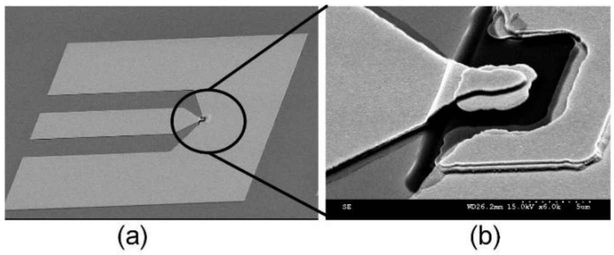


Fig. 3. (a) Fabricated single RTD device with bonding pads. (b) The central device size is about 16 μm^2.

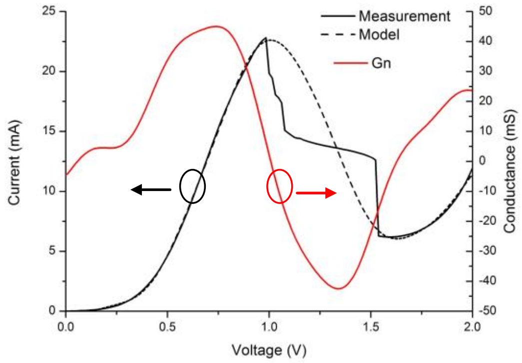


Fig. 4. The measured (–) and modeled (--) device DC characteristics. The negative differential conductance G_n is denoted in red line. Note that the G_n is negative across the entire NDR region with a minimum value of -42.5 mS.

B. Double RTD oscillator design and measurement

The high power RTD oscillator design proposed here employs two RTDs in parallel. The schematic circuit diagram of the oscillator is as shown in Fig. 5 (a), where R_e is the stabilizing resistor to suppress the low frequency bias oscillations. The bypass capacitor C_e is included in order to short the RF signal to ground at the designed oscillation frequency. Inductor L is designed to resonate with the RTDs' self-capacitance in order to determine the oscillating frequency. R_L is the load resistance. Fig. 5 (b) shows the RF equivalent circuit where assuming RTD1 and RTD2 are identical. The RTD is represented by contact resistance R_s in series with negative conductance G_n and self-capacitance C_n which are in parallel [6]. The total capacitance $C_n^* = 2C_n$, negative conductance $G_n^* = -2G_n$, and series resistance $R_s^* = R_s/2$.

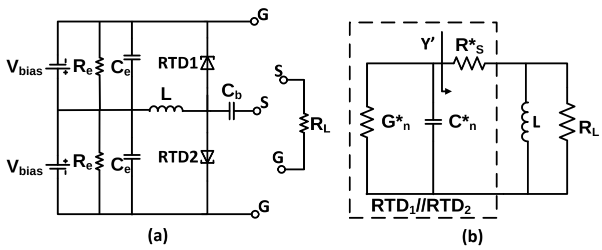


Fig. 5. (a) The schematic circuit of an oscillator employing two RTDs, each with its own DC stabilization circuit R_e and C_e. (b) Oscillator RF equivalent circuit.

The oscillator frequency f_o is determined by:

$$imag[Y'] + w_0 C_n^* = 0 \tag{1}$$

where Y' is the admittance as indicated in the circuit in Fig. 5b.

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

A micrograph of the fabricated circuit is shown in Fig. 6.

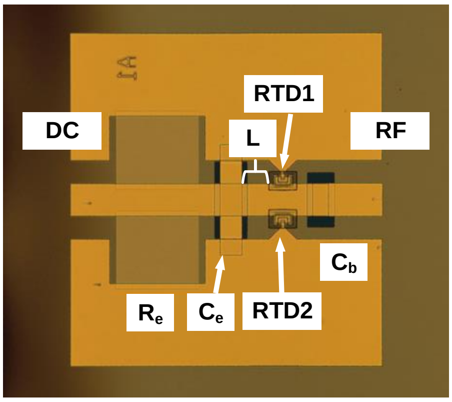


Fig. 6. Fabricated double RTD oscillator. 2RTDs are connected in parallel. Each device is biased individually with resistor R_e and bypass capacitor C_e. C_b is the DC block capacitor. The CPW length l =42 µm.

Each of the two RTD devices (RTD1 and RTD2) employed in the parallel oscillator circuit had an independent bias circuit. R_e was realized as a thin film NiCr (nichrome) resistor. The decoupling capacitor C_e was fabricated by using metal-insulator-metal (MIM) capacitor (C_e = 2 pF), with its dielectric layer SiN_x deposited by inductively coupled plasma (ICP) chemical vapor deposition (CVD). C_b was designed as a DC block capacitor with value C_b = 1.5 pF. The coplanar waveguide (CPW) structure with length of $l = 42\ um$ is terminated by C_e as shown in Fig. 7. From transmission line theory, it is known that the equivalent inductance L is given by (3) where Z_0 = 50 Ω, is the CPW characteristic impedance and β is the wave number.

$$L = \frac{Z_0 \tan(\beta l)}{2\pi f_0} \tag{3}$$

This designing approach is also applicable to higher frequencies which has been reported by our group at D-band (110-170 GHz) and J-band (220-325 GHz), respectively [7][8]. The oscillator was characterized on-wafer using Keysight's E4448A spectrum analyser. Since it is limited to 50 GHz, an external W-band mixer Keysight 11970W was used to down-convert the high frequency signal. When bias voltage V_{bias}=1.3V, bias current I_{bias}=88mA, the measured spectrum is shown in Fig. 7.

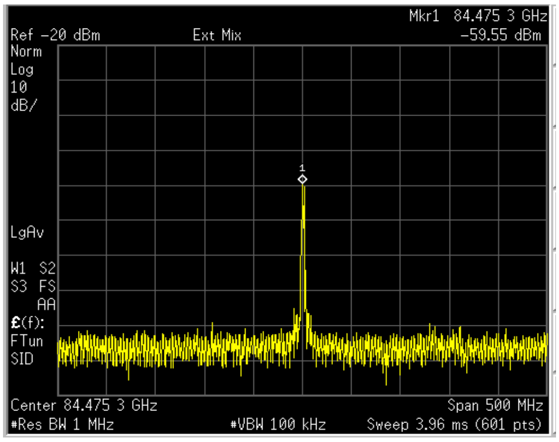


Fig. 7. When V_{bias}=1.3V, I_{bias}=88mA, the measured spectrum of 84.5 GHz oscillator.

As the mixer insertion loss is difficult to calibrate in the experiment, the actual oscillator output power was confirmed with the VDI Erickson PM5 power meter. The bias dependent frequency and power are plotted in Fig. 8. The central frequency is around 84.46 GHz, with a tunable range of about 150 MHz. The measured maximum power is about 2 mW. This is the highest power reported for a W-band RTD oscillator.

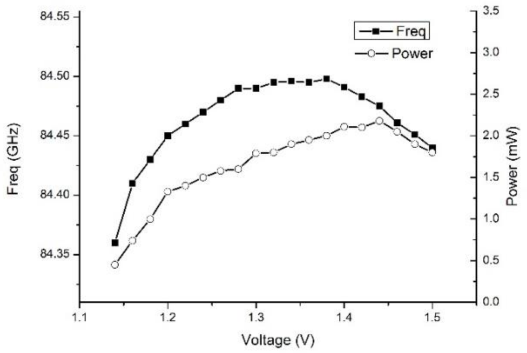


Fig. 8. The measured W-band RTD oscillator bias dependent frequency and output power. The frequency was about 84.46 GHz. The maximum power was about 2 mW.

The phase noise was also characterized on wafer using Keysight E4448A spectrum analyser as shown in Fig.9. The typical value is -79 dBc/Hz at 100 KHz and -96 dBc/Hz at 1 MHz offset of 84 GHz carrier. These values are better than many W-band CMOS techniques [9][10].

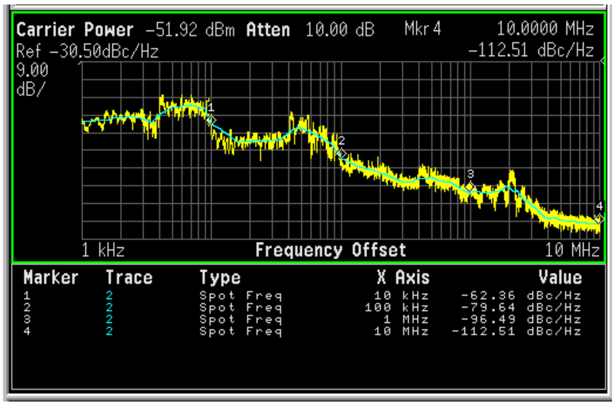


Fig. 9. Measured phase noise of the 84 GHz RTD oscillator. It is -79 dBc/Hz@100kHz and -96 dBc@1MHz.

IV. Wireless Measurement

The measurement setup is shown in Fig. 10. The 2^{15}-1 binary pseudorandom bit-sequence (PRBS) data is generated by using Keysight N4903B BERT. The data is fed from the DC side of the DUT through bias-tee. The transmitter output is connected through the RF probe to the horn antenna directly. The data is picked up by the receiver horn antenna and demodulated by an SBD detector. The distance between Tx and Rx was 50 cm. The output of SBD was amplified by a LNA and connected to the Keysight Infinium 86100C oscilloscope.

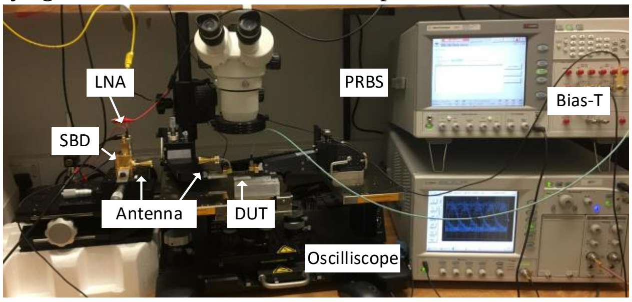
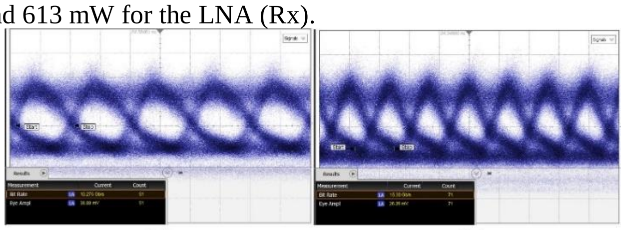


Fig. 10. Wireless communication measurement setup.

When the RTD is biased at 1.3V (88mA), the best results are obtained when data amplitude ranges between -200 mV and 200 mV. From the DC characteristics in Fig. 4, it is known that 1.3±0.2V still corresponds to the NDR region. The measured 10 Gbps and 15 Gbps eye diagrams are shown in Fig. 10 (a) and (b). The system's DC power consumption for Tx is 114.4 mW and 613 mW for the LNA (Rx).



(a) (b)

Fig. 11. When V_{bias}=1.2V, data amplitude was 400mV, ASK modulation (a) 10Gbps eye diagram (b) 15Gbps eye diagram.

The bit error rate (BER) was also measured. Up to 5 Gbps, the BER is around 1.0×10^{-6}, 3.6×10^{-4} for 10 Gbps, and 4.1×10^{-3} for 15 Gbps. The error free BER is expected up to 10 Gbps by optimizing measurement setup such as using high signal to noise ratio (SNR) LNA, etc.

V. Conclusion

A high power W-band RTD oscillator/transmitter was presented in this paper. Up to 15 Gbps ASK modulation over 50 cm wireless link has been demonstrated with correctable BER. Compared to other techniques, RTD transmitters provide a very promising simple, low cost, compact solution for future ultra-fast wireless communication systems. Efforts will be made to further improve the system's performance by employing on-chip high gain antennas, high responsivity detectors and high gain LNA, etc. It is expected that over 10 Gbps error-free wireless links over several meters in distance can be achievable.

Acknowledgment

The authors thank the staff of the James Watt Nanofabrication Centre (JWNC) at the University of Glasgow for help in fabricating the devices. This work was supported by the European Commission, grant agreement no. 645369 (iBROW project).

References

[1] P. Smulders, "The road to 100 Gb/s wireless and beyond: Basic issues and key directions," *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 86–91, 2013.

[2] T. Maekawa, H. Kanaya, S. Suzuki, and M. Asada, "Oscillation up to 1.92THz in resonant tunneling diode by reduced conduction loss," *Appl. Phys. Express*, vol. 9, no. 2, p. 24101, 2016.

[3] J. Lee, Y. Chen, and Y. Huang, "A low-power low-cost fully-integrated 60-GHz transceiver system with OOK modulation and on-board antenna assembly," *IEEE J. Solid-State Circuits*, vol. 45, no. 2, pp. 264–275, 2010.

[4] C. W. Byeon, C. H. Yoon, and C. S. Park, "A 67-mW 10.7-Gb/s 60-GHz OOK CMOS transceiver for short-range wireless communications," *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 9, pp. 3391–3401, 2013.

[5] K. Nakajima *et al.*, "23Gbps 9.4pJ/bit 80/100GHz band CMOS transceiver with on-board antenna for short-range communication," *2014 IEEE Asian Solid-State Circuits Conf. (A-SSCC)*, pp. 173–176, 2015.

[6] C. S. Kim and A. Brandli, "High-Frequency High-Power Operation of Tunnel Diodes," *IRE Trans. Circuit Theory*, vol. 8, no. 4, pp. 416–425, 1961.

[7] J. Wang *et al.*, "High Performance Millimetrewave Resonant Tunneling Diode Oscillator for THz applications," *IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS)*, pp. 1-4. 2015.

[8] J. Wang *et al.*, "High performance resonant tunneling diode oscillators as terahertz sources," *46th European Microwave Conference (EuMC)*, pp. 341–344, 2016.

[9] D. D. Kim *et al.*, "An array of 4 complementary LC-VCOs with 51.4% W-band coverage in 32nm SOI CMOS," *IEEE Int. Solid-State Circuits Conf.*, pp. 278–280, 2009.

[10] T. P. Wang, "A fully integrated W-band push-push CMOS VCO with low phase noise and wide tuning range," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 58, no. 7, pp. 1307–1319, 2011.