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Deposited on: 13 May 2019
15 Gbps Wireless Link Using W-band Resonant Tunnelling Diode Transmitter

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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 1.0×10⁻⁴, 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 Edholm’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 unlicensed 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 (Eg) 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 (Vp) 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.
B. Transceiver architecture

The transceiver block diagram is illustrated in Fig. 2.

![Transceiver Block Diagram](image)

**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 pads for measurement. Fig. 3 (b) shows the 16 µm² 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/cm² 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 $V_p = 0.9$V and valley voltage $V_v = 1.7$V, with a minimum value of $G_n$ of -42.5 mS.

![Resonant Tunneling Diode Device](image)

**Fig. 3.** (a) Fabricated single RTD device with bonding pads. (b) The central device size is about 16 µm².

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 $R_s$ is the stabilizing resistor to suppress the low frequency bias oscillations. The bypass capacitor $C_b$ 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. $R_s$ is the load resistance.

![Double RTD Oscillator Design](image)

**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.

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 $R_s$ is the stabilizing resistor to suppress the low frequency bias oscillations. The bypass capacitor $C_b$ 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. $R_s$ 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 $R_c$ 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 $R_s' = R_s/2$.

![Double RTD Oscillator RF Equivalent Circuit](image)

**Fig. 5.** (a) The schematic circuit of an oscillator employing two RTDs, each with its own DC stabilization circuit $R_c$ and $C_n$. (b) Oscillator RF equivalent circuit.
The oscillator frequency $f_o$ is determined by:

$$\text{imag}[Y'] + w_0 C_n^* = 0 \quad (1)$$

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

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

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

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 ($C_e = 2 \text{ pF}$), 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 $C_b = 1.5 \text{ pF}$. The coplanar waveguide (CPW) structure with length $l = 42 \mu \text{m}$ 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 $Z_0 = 50 \Omega$, is the CPW characteristic impedance and $\beta$ is the wave number.

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

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.

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.

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].
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The bit error rate (BER) was also measured. Up to 5 Gbps, the
BER is around $1.0 \times 10^{-8}$, $3.6 \times 10^{-4}$ for 10 Gbps, and $4.1 \times 10^{-3}$ 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).

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