22Gbps/80cm Low-Cost THz Wireless System

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***Abstract* — This paper presents 22 Gbps wireless link over 80 cm distance by using high power J-band resonant tunnelling diode (RTD) transmitter (Tx). The RTD Tx fundamental frequency is 278 GHz with around 1 mW output power. The system energy efficiency can reach 0.1 pJ per cm distance. No frequency multiplier, power amplifier or synthesizer was employed, and fabrication process is fully compatible with low-cost photo lithography. In addition, amplitude shift keying (ASK) modulation is used, this will also significantly reduce the system complexity hence the cost for high speed signal processing for both Tx and receiver (Rx).**

***Keywords* — resonant tunneling diode, RTD, wireless communication systems, ASK, oscillator, transmitter.**

I. Introduction

Nowadays there are exponential demands for high-speed wireless communication especially for applications such as 4K even 8K high resolution video transporting, 3D virtual reality (VR) and wireless connection in data centre, etc[1]. The expected peak wireless data rate by 5G is 20 Gbps, while in 6G it is 1,000 Gbps and a user experienced data rate of 1 Gbps [2]. Data rate of wireless communication is expected to merge with wired communication as depicted by Edholm's law [3]. Meanwhile power consumption, the cost including manufacturing and running cost are also becoming vital factors to be considered for daily life applications.

Since it is extremely difficult to achieve such high data rate within limited bandwidth using current microwave spectrum, it is preferable to shift the spectrum to unregulated THz regime around 300GHz to a few THz.

Currently the 300GHz transceiver technology can be divided into two groups: III-V compound semiconductor and silicon integrated circuits (IC). CMOS IC is normally limited by unity gain frequency f_{max} (the frequency at which power gain becomes unity) below or near 300GHz, great challenges exist in IC design to realize power amplifier (PA) and local oscillator at 300GHz. In addition, multistage multipliers (mixers) are required to generate 300GHz RF signal for CMOS IC [4].

Compared with many III-V semiconductor devices such as field effect or bipolar transistors (HEMTs or HBTs), or diode technologies (IMPATT, Gunn, etc.), the resonant tunnelling diode (RTD) has received considerable attention recently for realizing THz sources [2-7] because it has the highest demonstrated oscillation frequency of 1.92 THz [5]. It can operate at room temperature with compact size, and has the potential to be embedded within high speed optical network.

Recently, high data rate wireless transmission using RTDs has been reported by Asada's group who achieved 30~34 Gbps data rates by using amplitude shift keying (ASK)[6, 7]. Due to limited output power (26~60 μW @ 490 GHz), the link distance was only a few centimetres. Our group research focus is on increasing the power level of THz RTD oscillators meanwhile, to explore the full potential of RTD Tx for THz applications mentioned before. 2 mW at W-band (75-110 GHz) RTD Tx with 15 Gbps (BER of 10^{-3}) data rate over 50 cm and record high power of 1 mW at 260GHz RTD Tx have been reported in Refs. [8, 9].

In this paper we present 22 Gbps wireless link with 80 cm distance utilizing high power RTD Tx. The carrier frequency is 278 GHz. To the best of the authors' knowledge, this is the longest distance achieved at such high date rate by using RTD technology. RTD Tx fabrication process is fully compatible with low-cost photolithography (compared to electron-beam lithography). The power consumption of RTD Tx is about 200 mW at 1.5V bias voltage while zero power consumption for commercial Schottky barrier diode (SBD) receiver (Rx).

II. Transmitter Design and Receiver

A. RTD devices

The RTD device epitaxial layer consists of a 4.5 nm InGaAs quantum well sandwiched between double 1.4 nm AlAs barriers. The central device mesa size is 16 um^2 as shown in Fig.1 inset. The device was fabricated using photo lithography. The details can be found in [8, 9]. The measured I-V characteristic of the device is shown in Fig. 1. Due to parasitic oscillations when RTD was biased in the negative differential resistance (NDR) region, the measured I-V shows a plateau-like feature. The peak current density J_p is about 340 kA/cm^2 and the peak to valley current ratio (PVCR) is around 4. The single device maximum power can be estimated by [10]

$$P_{max} = \frac{3}{16}\Delta V \Delta I$$

where ΔI= 39 mA and ΔV= 0.6 V are the peak-to-valley current and peak-to-valley voltage differences, respectively. The estimated maximum power is 4.3 mW. Due to optimized fabrication process with low contact resistance, the estimated power is about 1.4 times higher than author's previous results in [10].

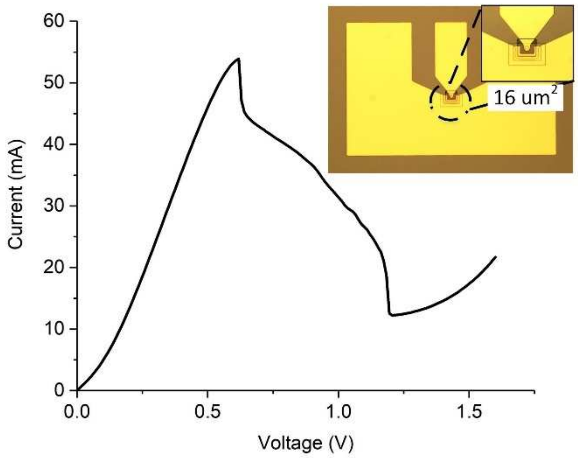

Fig. 1. Measured IV characteristics of the RTD device. J_p is about 340 kA/cm^2 and PVCR is about 4. Inset is the micrograph of the fabricated RTD devices with central device size 16 um^2.

B. *RTD 278GHz transmitter and SBD receiver*

The RTD oscillator design approach presented here employs a single RTD device as shown in Fig. 2. The shunt NiCr film resistor R_e is used to suppress the low frequency bias oscillations and the bypass MIM (metal-insulator-metal) capacitor C_e is used to ground the RF signal. The inductance L was realized by using a microstrip transmission line short stub. The design details can be found in [9] . When microstrip length = 47 µm, the measured 278 GHz RTD Tx spectrum is shown in Fig. 3. As the conversion loss of the harmonic mixer (OML, model M03HWD) is around 67-71 dB as shown in Fig. 4, the estimate Tx power is around 0.5-1 mW.

The receiver utilized in this experiment is commercial zero bias SBD envelop detector from Virginia Diodes, Inc (VDI). The typical responsivity can reach 2200 V/W and typical noise equivalent power (NEP) is about 12 pW/√Hz.

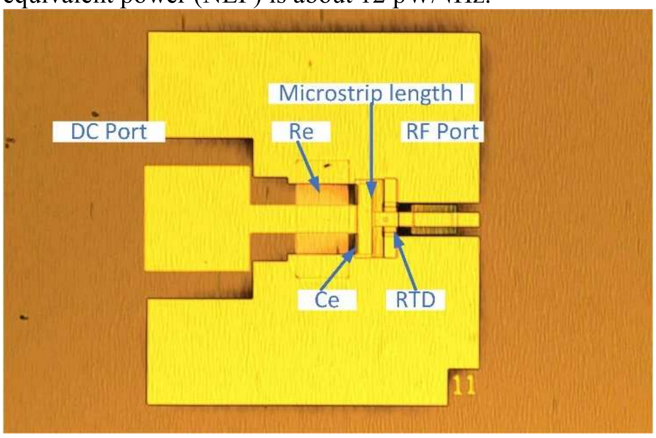

Fig. 2. Micrograph of a fabricated RTD oscillator circuit.

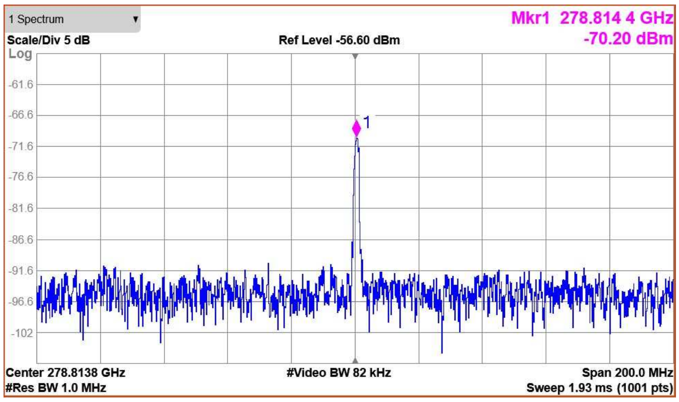

Fig. 3. Measured 278GHz RTD Tx spectrum when RTD was biased at 1.5V/134mA.

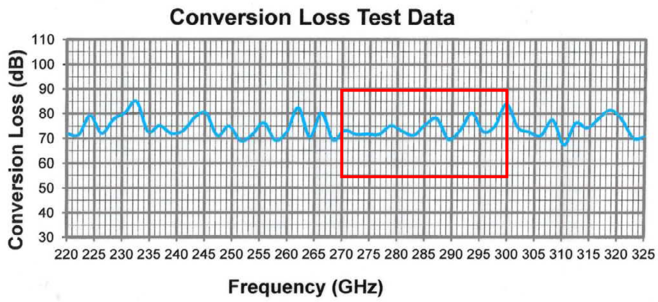

Fig. 4. Conversion loss of OML (model M03HWD) mixer.

III. Wireless System

A. *RTD Tx wireless system diagram*

The modulation scheme of RTD Tx is amplitude shift keying (ASK) as illustrated in Fig. 5. When RTD was biased in the middle of NDR region, non return zero (NRZ) data was applied through DC bias to modulate the amplitude of the carrier. Compared with FSK/QAM, ASK modulation offers higher bandwidth efficiency, simpler transmitter/receiver design hence less expensive signal processing approach for both transmission and reception.

The block diagram of the wireless system is shown in Fig. 6. The 2^{23}-1 PRBS (pseudo-random binary sequence) data is superimposed through bias-T on DC bias of the RTD Tx. The corresponding modulated output is transmitted through waveguide horn antenna. THz Polytetrafluoroethylene (PTFE) lens are utilized to collimate the beam. Since the fundamental frequency Tx can reach near 300 GHz with reasonable power, no mixer or power amplifier (PA) was required or employed in our current experiment. On the Rx side, the signal is demodulated by SBD envelope detector and amplified by low noise amplifier (LNA) manufactured by VDI. No synthesizer is required in this system.

B. *Link budget*

When RTD Tx output power is 0 dBm (1 mW); the measured power over 1 meter distance through PTFE lens was 40 uW. The antenna gain is about 26 dBi given by the manufacturer, which is the same for both Tx and Rx; the total Tx/Rx gain including antenna and PTFE lens can be estimated to be 38 dBi. Tx link loss is estimated to be 5 dB including RF probe insertion loss, waveguide connection loss and antenna misalignment. The Rx loss is estimated to be 3 dB including the connection and cable loss. For the SBD detector, the minimum required power for the diode working in square-law region is in the range of 3-5 μW [11]. Therefore, given the transmitter power, the calculated maximum allowable free space path loss is 17 dB which corresponds to a distance of around 4 meters at 278 GHz. If high gain (50 dBi) antenna was utilized as in [12], 50 meters distance wireless link can be achieved.

C. *Measurement results*

The lab setup is shown in Fig. 7. The modulated RF signal is transmitted and collimated through THz PTFE lens. The link distance is about 80 cm. The measured eye diagram of 12 Gbps (error free) and 22 Gbps (BER=10^{-3}) is shown in Fig. 8 and Fig. 9 respectively.

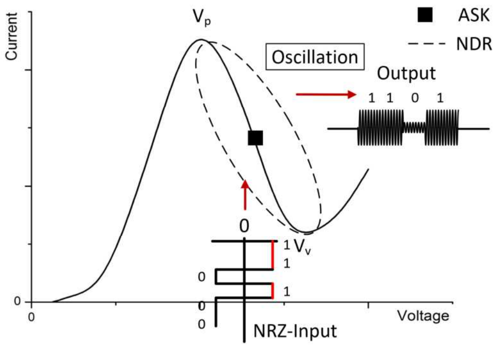

Fig. 5. The illustration of RTD Tx ASK modulation.

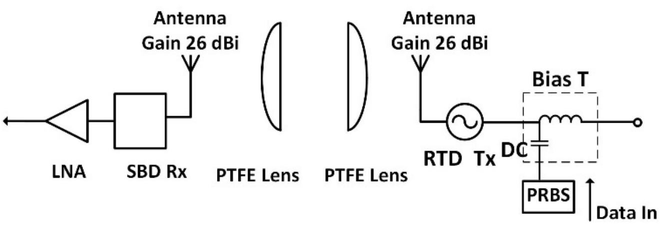

Fig. 6. Block diagram of the wireless system architecture.

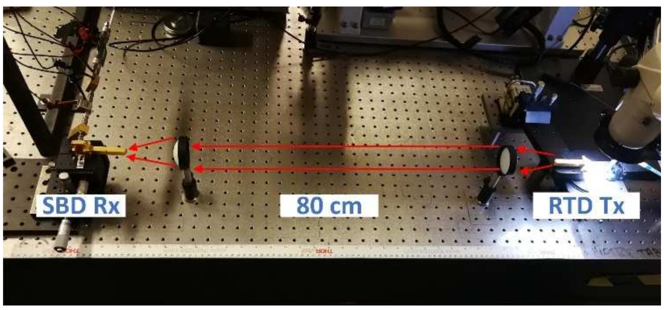

Fig. 7. RTD Tx (278GHz) SBD Rx 80 cm wireless system lab setup.

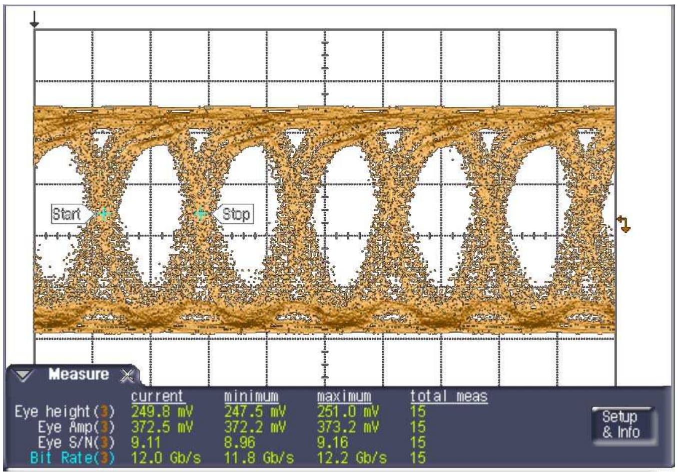

Fig. 8 12 Gbps error free eye diagram over 80 cm.

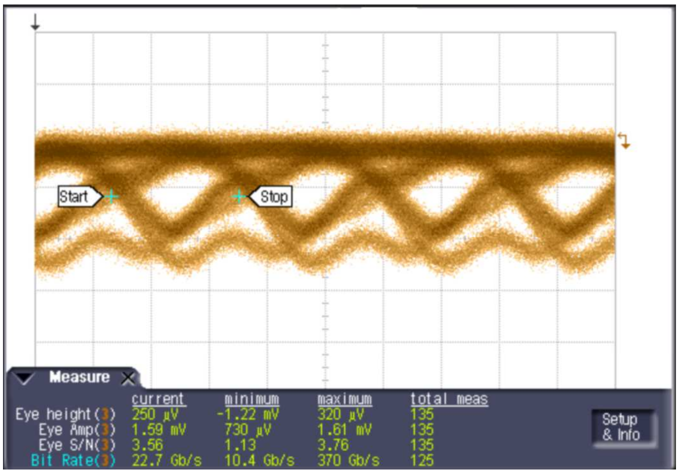

Fig. 9. 22 Gbps (BER=10^{-3}) eye diagram over 80 cm.

Table I compares this work with up to date high speed THz wireless link including CMOS [4], InP-HEMT [12, 13] and RTD [7, 14, 15] technologies. Our work present low power consumption and long link distance with simple system architecture.

IV. Conclusion

22 Gbps wireless system using RTD THz transmitter with 80 cm distance has been demonstrated in this paper. The total power consumption of Tx and Rx is 200 mW. As no mixer, PA or synthesizer was used in the system, which greatly simplify the system design, the design and running costs are significantly reduced. The preliminary results presented in this paper demonstrate RTD Tx a very promising future as simple, low cost, compact transmitter for future ultra-fast wireless communication systems. With further optimization of the system, such as RTD device packaging, high gain antenna, smart antenna array design for beam forming, the link distance is expected to reach as far as tens of meters while the data rate can approach 100 Gbps in near future.

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Table 1. Performance comparison

Design	**[4]**	**[12]**	**[13]**	**[7]**	**[14]**	**[15]**	**This work**
Technology	40 nm CMOS	80 nm InP-HEMT	80nm InP-HEMT	RTD	RTD	RTD	RTD
Carrier Frequency	265GHz	270GHz	300GHz	490GHz	490GHz	286GHz	278GHz
Modulation	16QAM	16QAM	ASK	ASK	ASK	ASK	ASK
Power Dissipation	1.79W	-	-		100 mW	-	200 mW
Tx output power	-1.6 dBm	-	-	60 μW	60 μW	-	1 mW
PA	no	yes	yes	no	no	no	no
Antenna Gain	24 dBi	50 dBi	-	-	-	-	26
Data Rate	80Gbps	100Gbps	20Gbps	22/34Gbps	28Gbps×2 channels	12Gbps	22Gbps
Distance	3cm	2.22m	Back to back	20-30 cm	20 cm	10 cm	80cm
EVM/BER	12%	38%	10^{-9}	10^{-3}	10^{-3}-10^{-4}	10^{-3}	10^{-3}
Energy Efficiency /distance	7.5pJ/bit*cm	-	-	-	0.2pJ/bit*cm	-	0.1pJ/bit*cm
Chip Size including testing pads	2.2×4.9 cm^2	Mixer: 1mm×1mm	-		-	-	RTD Tx: 0.5×0.5 cm^2