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28 GHz MMIC resonant tunnelling diode oscillator of around 1mW output power

J. Wang, L. Wang, C. Li, B. Romeira and E. Wasige

Presented is a monolithic microwave integrated circuit (MMIC) resonant tunnelling diode (RTD) oscillator that employs two InGaAs/AlAs RTDs (5 × 5 µm²) in parallel. The oscillator works at 28.7 GHz with −0.7 dBm output power. The phase noise was −95 dBc/Hz at 100 kHz and −114 dBc/Hz at 1 MHz offset. This reported work demonstrates the potential of RTD oscillators in achieving high output power at high frequencies by utilising suitable power maximising and combining techniques.

Introduction: Resonant tunnelling diodes (RTDs) are the fastest solid-state electronic devices demonstrated to date. They are promising for realising terahertz (THz) sources operating at room temperature [1, 2]. However, the output power of RTD based oscillators tended to be low due to parasitic bias oscillations and small device dimensions. The output power of the single RTD (0.35 µm²) oscillator operating at a record 1.1 THz is only 0.1 µW [3].

In this Letter, a monolithic microwave integrated circuit (MMIC) RTD oscillator employing two 5 × 5 µm² devices with high output power is presented. Compared with single RTD device oscillators and spatial power combing techniques reported previously [2, 3], here two large mesa size RTDs were combined at circuit level to maximise the output power. Each RTD had a separate DC decoupling circuit to suppress low frequency bias oscillations. The fundamental frequency of the fabricated oscillator was 28.7 GHz with −0.7 dBm (0.85 mW) output power. It is anticipated that a similar circuit topology can be utilised at higher frequencies to achieve higher output powers.

Device characteristics and circuit description: The material (InGaAs/AlAs) of the diode was grown by molecular beam epitaxy (MBE) on a semi-insulating InP substrate. It consists of a 5.5 nm InGaAs quantum well sandwiched between 1.4 nm AlAs double barriers. The quantum structure including the spacer layer. The oscillator simulation was simulated in Agilent Advanced Design System (ADS2009) software. The RTD was modelled by the small signal equivalent of the oscillator circuit is shown in Fig. 1, which shows the IV characteristic of the fabricated device. The peak current density was 72 kA/cm² and the peak-to-valley current ratio (PVCR) was about 2.5.

Fig. 1 IV characteristic of fabricated RTD

The oscillator schematic is shown in Fig. 2 [4], where \( R_b \) and \( L_b \) denote the resistance and the inductance of the bias line, respectively. \( R_e \) is the stabilising resistor to suppress the low frequency bias oscillations. The decoupling capacitor \( C_d \) short-circuits the RF signal to ground to avoid loss of RF power in \( R_e \). Inductance \( L \) is chosen to resonate with the device capacitance to obtain the desired oscillating frequency. \( R_x \) is the load resistance.

Fig. 2 Schematic of oscillator employing two RTDs, each with its own DC stabilisation circuit \( R_x \) and \( C_x \)

The simulation result of two RTDs oscillator with \( R_x = 1.9 \Omega, L_b = 23 \text{ nH}, R_x = 26 \Omega, C_x = 58 \text{ pF}, L = 278.5 \text{ pH}, V_{bias} = 1.3 \text{ V}, R_L = 50 \Omega \)

Fig. 4 Simulation result of two RTDs oscillator with \( R_x = 1.9 \Omega, L_b = 23 \text{ nH}, R_x = 26 \Omega, C_x = 58 \text{ pF}, L = 278.5 \text{ pH}, V_{bias} = 1.3 \text{ V}, R_L = 50 \Omega \)

Experimental results and discussion: A micrograph of the fabricated circuit is shown in Fig. 5. The overall size of the oscillator circuit including contacting pads is about 1020 × 870 µm². \( R_x \) was realised as a thin film NiCr resistor (50 Ω/square sheet resistance, 33 nm thickness). The decoupling capacitor \( C_x \) was realised as a metal-insulator-metal (MIM) capacitor (\( C_x = 87.1 \text{ pF} \)). The dielectric layer was 75 nm SIN deposited by inductively coupled plasma (ICP) chemical vapour deposition (CVD). The shorted 710 µm-long CPW acts as inductance

The oscillator circuit was modelled with the circuit simulation software Agilent Advanced Design System (ADS2009) software. The RTD was modelled by the small signal equivalent circuit shown in Fig. 1. The circuit in Fig. 2 was simulated in Agilent’s Advanced Design System (ADS2009) software. The RTD was modelled by the IV measurement data shown in Fig. 1 (from a stabilised but identical device, i.e. smooth characteristic in the negative differential resistance (NDR) region), while the capacitance of the RTD which was estimated from its geometrical size by \( C_0 = \frac{\varepsilon e d}{A} = 26.7 \text{ fF} \) where \( e \) is the dielectric constant of InGaAs, \( S \) is the device mesa size and \( d \) is the width of the quantum structure including the spacer layer. The oscillator simulation result is shown in Fig. 4 for a (non-optimal) 50 Ω load.

To maximise oscillator power, the largest possible mesa sizes for RTDs that can be stabilised are used [5]. On the other hand, to increase the oscillator frequency, instead of reducing the diode size to reduce the self-capacitance \( C_0 \), the value of inductance \( L \) can be chosen by an appropriate length of the coplanar waveguide (CPW).

Fig. 3 Oscillator small signal equivalent circuit excluding RTD parasitic elements

The small signal equivalent of the oscillator circuit is shown in Fig. 3, where \( -G_{1n}, -G_{2n} \) are the negative differential conductance of RTD1 and RTD2, while \( C_{1n} \) and \( C_{2n} \) are the self-capacitances of each RTD. For simplicity, the RTD is modelled by its negative differential resistance and its capacitance. For this parallel resonant circuit, the oscillation frequency can be determined by equating the circuit susceptance to zero, i.e.

\[
\frac{1}{j2\pi f_{osc} L_1} + \frac{j2\pi f_{osc} (C_{1n} + C_{2n})}{C_{1n} + C_{2n}} = 0, \quad \text{from which}
\]

\[
f_{osc} = \frac{1}{2\pi \sqrt{(C_{1n} + C_{2n})/L_1}}
\]

Experimental results and discussion: A micrograph of the fabricated circuit is shown in Fig. 5. The overall size of the oscillator circuit including contacting pads is about 1020 × 870 µm². \( R_x \) was realised as a thin film NiCr resistor (50 Ω/square sheet resistance, 33 nm thickness). The decoupling capacitor \( C_x \) was realised as a metal-insulator-metal (MIM) capacitor (\( C_x = 87.1 \text{ pF} \)). The dielectric layer was 75 nm SIN deposited by inductively coupled plasma (ICP) chemical vapour deposition (CVD). The shorted 710 µm-long CPW acts as inductance
L. $R_L$ was introduced by the input impedance of the spectrum analyser, $50 \, \Omega$. The MMIC RTD oscillator was measured on-wafer using a GSG probe (DC-40 GHz) from Cascade and the HP8564E spectrum analyser from Agilent.

Fig. 5 Photograph of fabricated two RTDs oscillator

When the bias voltage was 1.42 V, the total bias current was 203.6 mA, the measured oscillation frequency was 28.7 GHz with $\sim -5.8 \, \text{dBm}$ output power at the spectrum analyser (Fig. 6). After compensating the probe, cable, and bias-T loss, the actual output power is about $\sim 0.7 \, \text{dBm}$, which is the highest power reported for a Ka-band RTD oscillator. Good agreement between simulation and experiment was achieved. The phase noise of the RTD oscillator was also measured (Fig. 7). It was $\sim -95 \, \text{dBc/Hz}$ at 100 kHz and $\sim -114 \, \text{dBc/Hz}$ at 1 MHz offset. This is 3 dB better at 100 kHz and 8 dB worse at 1 MHz compared to a Ka-band low phase noise HEMT oscillator [6], but it is of the same order as that of the lowest reported RTD-based oscillator [7].

Fig. 6 Measured output spectrum of oscillator employing two RTD devices at bias voltage of 1.42 V, total current is 203.6 mA, span = 100 MHz

Fig. 7 Measured SSB phase-noise at 28.75 GHz carrier frequency

Conclusion: A MMIC RTD oscillator which combined two large RTD devices ($5 \times 5 \, \mu\text{m}^2$) for high output power has been described. Good oscillator performance such as high power output and low phase noise was demonstrated for RTD material with modest peak current density and an unmatched oscillator load. The results demonstrate the potential of this technology for higher power ($>1 \, \text{mW}$) and frequency ($>100 \, \text{GHz}$) by proper circuit design as discussed in [5]. Such oscillators are expected to be useful in applications such as imaging and wireless communication systems owing to high frequency, high power and low phase noise performance. Note however that owing to the large portion of DC power that is consumed by the stabilisation resistor $R_s$, the DC to RF conversion efficiency is low, 0.29% here. Future work will address this by considering various options including Schottky diode stabilisers, using RTD material with low peak voltage etc.

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