Short Article

Terahertz Resistor-coupled Arrayed Resonant-tunneling-diode Oscillators with High DC-to-RF Efficiency using Metal-insulator-metal Capacitor

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Abstract– **Resistor-coupled arrayed resonant-tunneling-diode (RTD) oscillators have emerged as a promising candidate for high-performance Terahertz sources. Despite various advantages, the DC-to-RF efficiency of such oscillators is still low. The reason is the loss caused by resistors, which form the ends of the slot antennas. This paper presents a method to increase the DC-to-RF efficiency of resistor-coupled arrayed oscillators. Edged resistors at the ends of slot antennas are covered by metal-insulator-metal capacitors, which shunt the currents flowing through those resistors. Thus, the conduction loss caused by edged resistors is reduced. Owing to low conduction loss, high output power is obtained, resulting in a high DC-to-RF efficiency. It is estimated that the proposed oscillator's output power and DC-to-RF efficiency reach 1.53 mW and 0.44% at 450 GHz, respectively. A high power density of up to 62 mW/mm2 is another advantage of the proposed RTD oscillator. With the improved characteristics, we believe the proposed oscillators could promote various Terahertz applications.**

Keywords– **Terahertz waves, Resonant-tunneling-diode, DC-to-RF efficiency.**

1 Introduction

Recently, much interest has been given to terahertz (THz) waves, which are electromagnetic radiations with frequencies ranging from 100 GHz to 10 THz. THz waves reveal unique features including extremely wide available bandwidth, penetrating through non-conducting materials, and exhibiting "fingerprints" to organic cells. These features are the origin of various promising applications of THz waves such as high-data-rate wireless communications [1–3], imaging [3–6], spectroscopy [7, 8], and sensing [9, 10]. THz frequency range is also well-known for the "THz gap", which relates to the difficulties in generating and detecting the THz waves. Many candidates for THz commercial sources have been investigated. THz sources can be divided into optical-based and electronic-based ones. From the optical side, quantum-cascade-laser (QCL) is an important candidate with high frequency and high output power [11, 12]. However, the limitation of QCLs is low-temperature operation, which requires cryogenic cooling. From the electronic side, Gunn diodes [13], IMPATT-TUNNET diodes [14], new-generation transistors [15–17], and resonant-tunneling-diode (RTD) oscillators have been considered. Among them, RTD oscillators are a good candidate because of their high oscillation frequency, room-temperature operation, and compact size [18–20]. Recently, arrayed RTD oscillators with a coupled resistor for anti-phase coupling between two adjacent array elements have been investigated intensively [21–23]. Such RTD oscillators exhibited output powers of milliwat level, making them closer to practical applications. However, reported resistor-coupled arrayed RTD oscillators exhibited a relatively low DC-to-RF conversion efficiency of 0.22% [21]. For applications where battery capacity is limited such as mobile ones, higher DC-to-RF conversion efficiency is highly desirable. One contributing reason for the relatively low DC-to-RF conversion efficiency is the high conduction loss caused by the resistors at the edges of slot antennas. In this paper, we propose a method to reduce the conduction loss caused by these resistors, which is obtained by covering a metal-insulator-metal (MIM) structure on these resistors. Owing to a reduction in the conduction loss, higher output power is achieved, thus enhancing the DC-to-RF efficiency. The powerful tool Ansys HFSS is utilized for 3D electromagnetic simulation. Theoretical calculations show that a DC-to-RF conversion efficiency of 0.44% is achieved owing to a decrease in the conduction loss.

2 Structure and Operation of the Proposed Arrayed RTD Oscillators

The proposed RTD oscillator is constructed on an indium phosphide (InP) substrate, which is popular for ultra-high-speed devices operating in the THz region. The arrayed structure includes two elements coupled to each other via a common resistor as shown in Figure 1.

Each element forms a single oscillator composed of an AlAs/InGaAs double-barrier RTD mesa and a

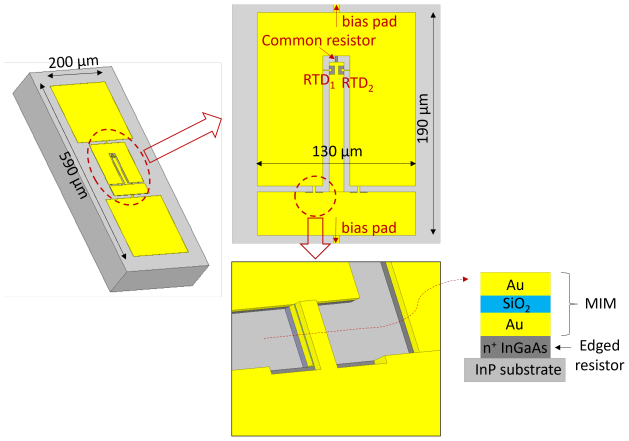

Figure 1. Device structure of the proposed RTD oscillator.

slot antenna. The slot antenna plays roles both as a resonator for THz standing waves and as a radiator. The RTD epitaxial layers are grown on the InP substrate to form a double barrier structure, which is sandwiched by a quantum well. The RTD exhibits a negative differential conductance (NDC), which compensates for the loss caused by the slot antenna for a THz oscillation. The antenna loss includes the conduction loss G¬loss and the radiation conductance Grad. The oscillation frequency is determined by the resonance of the tank circuit including the RTD capacitance and the resonator inductance. The oscillation condition for a single RTD oscillator can be derived from the equivalent circuit depicted in Figure 2 by $G_{rtd} > G_{loss} + G_{rad}$.

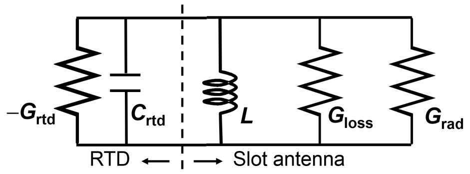

Figure 2. Equivalent circuit of single RTD oscillator.

To suppress low-frequency parasitic oscillations, shunt resistors, which are parallelly connected with RTD, are employed. Those resistors have to cancel the RTD negative conductance for this purpose, which means $1/R_{sup} > G_{rtd}$. For structure-simplified RTD oscillators, suppressed resistors are usually placed at the ends of slot antenna to form reflectors [21, 24].

The slot antennas used in the proposed structure are offset-fed ones, which means the RTD position is shifted from the center of the corresponding slot antenna. The offset-fed slot antenna includes a short slot antenna connected in parallel with a long slot one. The short one dominantly contributes to the slot inductance, and therefore the oscillation frequency. The long one dominantly contributes to the slot radiation conductance, and therefore the output power. In this work, we limit the frequency range of interest from 400 to 600 GHz because this THz window exhibits wide bandwidth and relatively low transmission loss [25]. Thus, the antenna length and offset position are selected to achieve the maximum output power at approximately 500 GHz.

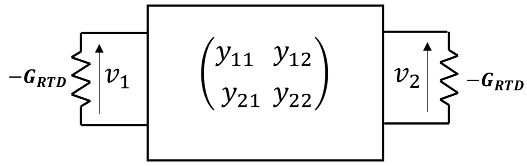

Figure 3. Two-element arrayed oscillator as a two-port network.

The two-element arrayed oscillator can be represented by a two-port network as depicted in Figure 3. The admittance matrix of a two-element arrayed oscillator is written as

$$Y = \begin{pmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{pmatrix}. \tag{1}$$

For a symmetrical array, one has $y_{11} = y_{22}$ and $y_{12} = y_{21}$. It was found that $\gamma_1 = y_{11} + y_{12}$ and $\gamma_2 = y_{11} - y_{12}$ are the two eigenvalues of the Y matrix of the two-element array. Because of strong coupling between array elements via the common resistor, various operation modes can occur. For a two-element arrayed RTD oscillator, there are two possible operation modes [21]. They are odd mode and even mode. Two RTDs are anti-phased in the odd mode, while they have the same phase in the even mode. The eigenvalue γ_1 corresponds to the even mode, while the eigenvalue γ_2 corresponds to the odd mode. The AC currents flowing through the common resistor have the same directions in the even mode, resulting in a high loss in the common resistor. Whereas, these currents cancel each other in the odd mode, resulting in a very small loss in the common resistor. It has been proved that the odd mode is more stable than the even one thanks to the low loss in the common resistor [21].

In the odd mode operation, the output power is calculated by the following formula [21]

$$P_{total} = \frac{4}{3b} G_{rad} \left(a - Re\left[y_{11} - t_{12} \right] \right), \tag{2}$$

where, b is a coefficient which is determined via the current width ΔI and voltage width ΔV of the NDC region of the RTD as $b = \frac{2\Delta I}{\Delta V^3}$. The $Re\left[y_{11} - y_{12}\right]$ component is the sum of the radiation conductance G_{rad} and the conduction loss G_{loss}. The output power of the RTD arrayed oscillator is estimated by

$$P_{\text{total}} = \frac{4}{3b} G_{\text{rad}} \left(a - G_{\text{rad}} - G_{\text{loss}} \right). \tag{3}$$

It is clear that to enhance the output power, it is necessary to decrease the conduction loss [18]. It was pointed out that for the structure-simplified RTD oscillators, the conduction loss is proportional to the suppressed resistors [24]. As mentioned above, because the currents caused by the two RTDs flowing through the common resistors cancel each other, hence, the loss in the common resistor is very small in the odd mode operation. The conduction loss in the suppressed resistors is mostly caused by the edged resistors because of the high current density in these resistors as shown in Figure 4(a). Therefore, in this article, we propose a method to effectively reduce the loss caused by the edged resistors.

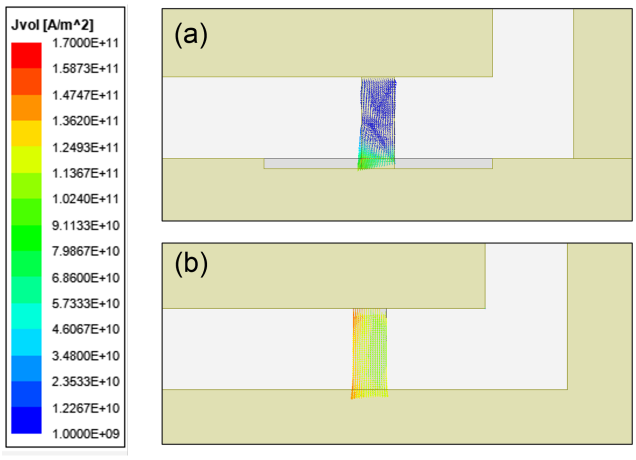

Figure 4. Current distribution in edged resistors (a) with covering MIM capacitor and (b) without covering MIM capacitor.

To do that, we cover the edged resistors with MIM structures. An MIM structure is indeed a capacitor. Because the MIM capacitor makes an AC short circuit at the end of the slot antenna, there is almost no current flowing through the edged resistors as demonstrated in Figure 4(b), resulting in a low conduction loss. This argument is also verified by the calculated conduction losses, which are obtained from the powerful 3D electromagnetic simulator Ansys HFSS. The calculated conduction losses for the RTD oscillators with and without the MIM capacitor are plotted in Figure 5.

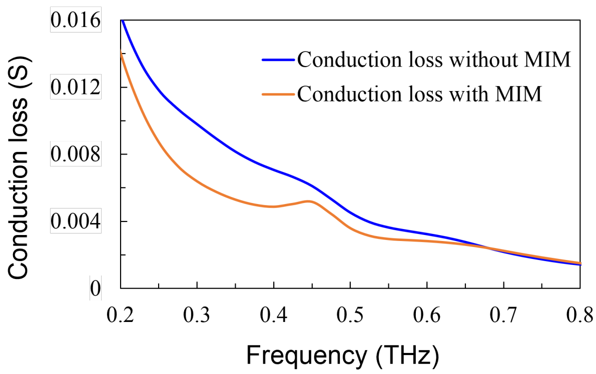

Figure 5. Calculated conduction loss of RTD arrayed oscillators with and without covering MIM capacitors.

3 Results and Discussion

We estimate the output power of RTD arrayed oscillators using formula (2), where the components of the antenna loss were obtained from the 3D electromagnetic simulator Ansys HFSS. RTD parameters including the current width, the voltage width, and the peak-to-valley ratio (PCVR) used for calculating the output powers are 12 mA/μm^2, 0.4 V, and 2.5, respectively. These parameters are the same as those used in the Reference [21] for a fair comparison.

The calculated output powers of the RTD oscillators with and without the MIM capacitor are shown in Figure 6. As can be seen, in the frequency range of interest, the proposed RTD oscillator, which is with the covering MIM capacitor, exhibits a greater output power than that of the one without the MIM capacitor. The highest output power of the proposed RTD oscillator is 1530 µW at 450 GHz. While in the frequency range of interest, the RTD oscillator without an MIM capacitor exhibits the highest output power of 1030 µW at 480 GHz.

The DC power consumption of an RTD oscillator includes the power consumed by the shunt resistors and the output power radiated by RTDs. Among them, the former is dominantly large compared to the latter. For a fixed oscillation frequency, the bias voltages for the two types of RTD arrayed oscillators are considered equal. Moreover, shunt resistors to suppress low-frequency parasitic oscillations for the proposed and previous RTD arrayed oscillators are the same. Hence, the DC power consumptions are identical for both RTD oscillator types. It can be estimated from Reference [21] that the DC power consumption was 344 mW for the RTD arrayed oscillator w/o MIM capacitors. Thus, in this study, we assumed the DC power consumption is 344 mW for both RTD arrayed oscillators w/ MIM and w/o MIM.

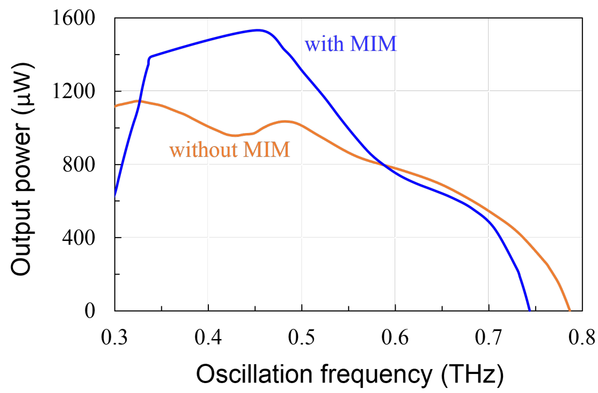

Figure 6. Output power as a function of the oscillation frequency.

The DC-to-RF efficiency is calculated as the ratio of the output power to the DC power consumption. One can deduce that in the frequency of interest, the DC-to-RF conversion efficiency of the proposed structure is better than that of the previous structure as depicted in Figure 7. The highest theoretical DC-to-RF conversion efficiency for the structure without MIM is estimated at 0.299% at 480 GHz. For the proposed structure, at the same oscillation frequency, that figure is 0.413%, and the highest one is estimated at 0.444% archived at 450 GHz. The calculated results at various frequencies in the frequency range of interest are summarized in the Table I.

As mentioned above, the bias voltage can be assumed to be the same for RTD oscillators with MIM and without MIM. So actually, output powers and DC-to-RF efficiency of the two types of RTD oscillators were compared with the same bias voltage condition.

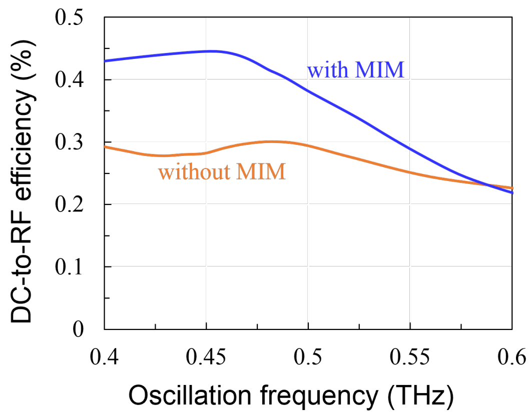

Figure 7. DC-to-RF efficiency of RTD arrayed oscillators.

It is safe to conclude that the proposed RTD arrayed oscillator with MIM capacitor covering edged resistors outperforms the previous RTD arrayed oscillator in terms of output power and DC-to-RF efficiency. In Figure 6 and Figure 7, the oscillation frequency of RTD oscillators can be changed by varying the RTD capacitance. In practice, various RTD mesa areas are fabricated to realize RTD capacitance variation.

The slot antennas used in the proposed RTD oscillator have a hybrid type, in which one reflector of the slot antenna is a resistor and the other is a resistor covered by an MIM capacitor. To the best of our knowledge, this is the first time, a hybrid type of slot antenna has been proposed for an RTD oscillator. Another advantage of the proposed RTD oscillator is its high power density, which is defined as the ratio of the output power to the chip area. This is clearly shown in the Table I. This was achieved because of the small chip size and high output power. A high power density of up to 62 mW/mm2 allows the arrangement of a large number of chip elements in a small area. By employing MIM capacitors, the fabrication process become more complex. Additional electron beam lithography, silicon dioxide passivation, and gold evaporation are required for MIM fabrication. This is, however, not a problem for massive fabrication in the semiconductor industry.

Table I
Chip Size and Power Density of Various RTD Oscillators

Ref.	This work	[19]	[21]	[26]	[27]	[28]
Chip size (mm^2)	0.0247	10	0.0247	2.2	0.12	0.13
Power density (mW/mm^2)	61.9*	1.2	31 41.7*	0.33	8.3	0.08

*Theoretical calculation.

4 Conclusion

In this article, we proposed a method to improve the DC-to-RF conversion efficiency. The edged resistors of the slot antennas were covered by MIM structures, which helps to reduce the conduction loss. This results in an increase in the output power and consequently an improvement in the DC-to-RF conversion efficiency. The proposed RTD oscillator with a novel hybrid type slot antenna exhibits a relatively high DC-to-RF efficiency of 0.444% at 450 GHz. The proposed RTD oscillator is also advantageous thanks to its high power density of up to 62 mW/mm2. Owing to these improved characteristics, the proposed RTD arrayed oscillator is promising for various THz applications owing to yielding a longer battery lifetime and compact size.

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