Direct intensity modulation of resonant-tunneling-diode terahertz oscillator up to \(~30\) GHz

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Abstract:
We proposed and fabricated resonant-tunneling-diode (RTD) terahertz (THz) oscillators with a structure for high-frequency direct modulation, which is useful for high-capacity THz wireless communications. The oscillator is composed of RTD and slot antenna. To obtain high cut-off frequency of direct modulation, the capacitance of the metal-insulator-metal (MIM) layer forming the slot antenna was reduced without decrease in THz output power which was a problem in the previous structure. A cut-off frequency of 30 GHz was obtained in direct intensity modulation of the device oscillating at 350 GHz with the reduced MIM capacitance of 0.7 pF.

Keywords: terahertz oscillators, terahertz communications, resonant tunneling diode, high-frequency direct modulation

Classification: Microwave and millimeter wave devices, circuits, and systems

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1 Introduction

The terahertz (THz) frequency range of roughly 0.1-10 THz has received considerable attention, because various applications are expected [1, 2]. In particular, high-capacity short-distance wireless communication using the wide band of the THz range is an important application. Demonstrations of the THz communication have been intensively carried out [3, 4, 5, 6, 7].

Compact and coherent solid-state sources are key components for such an application. Resonant tunneling diodes (RTDs) are one of the candidates for these sources [8, 9, 10, 11, 12, 13, 14]. Room-temperature fundamental oscillation up to 1.55 THz and relatively high output power of 610 µW at 620 GHz with a two-array configuration have been achieved [15, 16]. Wireless data transmission with RTDs has also been demonstrated [6, 7]. RTDs are suitable for compact and simple sources in THz data transmission, because the output power is easily modulated by a signal superimposed on bias voltage.

In the previous experiments of the THz wireless transmission with RTDs, the data rate was limited up to a few Gbit/s due to the cut-off frequency of the direct modulation of RTD oscillators [6, 7]. Although the RTD has a wide-band response up to its oscillation frequency, external structures around the RTD, such as the structures for THz resonator and antenna, work as a low-pass filter to the external microwave signal, limiting the modulation frequency [6]. The cut-off frequency of modulation can be increased by improvement of the elements constructing the
low-pass filter. However, it is shown in this letter that this improvement brings on degradation of THz output power in the previous structure. We discuss this problem in detail, and propose an improved structure for high-frequency modulation. A cut-off frequency of 30 GHz is experimentally shown.

2 Problem of the previous RTD oscillator in high-frequency modulation

Fig. 1 shows the structure of the RTD oscillator used for wireless data transmission in [6]. The RTD has an InGaAs/AlAs double-barrier structure fabricated on a semi-insulating InP substrate. A slot antenna with the length of ~20 μm is integrated with the RTD as a resonator and a radiator. The left and right electrodes of the antenna are connected to the upper electrode and downside of the RTD. Both ends of the slot antenna are blocked with metal-insulator(SiO₂)-metal (MIM) layers to form reflectors for THz waves and to simultaneously achieve DC bias separation. A bismuth sheet resistance with the length of ~1mm is connected to the antenna electrodes at the outer side of the THz resonator. Due to this resistance, the negative differential conductance of the RTD cannot be seen from the circuit outside the oscillator, and thus, low-frequency parasitic oscillations caused by the combination of the external circuit and RTD are suppressed. The output power is radiated into the substrate side with high dielectric constant, and extracted through a hemispherical silicon lens.

The output power of the RTD oscillator can easily be modulated by a signal superimposed on the bias voltage [6]. The circuit for this purpose is also shown in Fig. 1. The equivalent circuit of the oscillator for modulation frequency (about 1-100 GHz) is shown in Fig. 2. $R_s$ and $L_{wire}$ are the output resistance of the modulation source and the inductance of bonding wires, respectively. The total capacitance of the MIM layers ($C_{MIM}$) and the equivalent elements of the sheet resistance ($R_{sup}$ and $L_{sup}$) are connected to the RTD expressed by the negative differential conductance $-G_{RTD}$. The slot antenna is neglected in Fig. 2, because it is much shorter than the wavelength of the modulation frequency.
The modulation voltage across the RTD decreases with increasing frequency due to the low-pass filter included in Fig. 2. In the previous experiment, the 3-dB cut-off frequency was limited to 1.1-4.5 GHz [6]. Among the elements of the low-pass filter, $C_{MIM}$ has a large influence, because it is directly connected in parallel with the RTD. A small $C_{MIM}$ can be obtained by reducing the area of the MIM layers. However, we found that the THz output power decreases with the reduction in $C_{MIM}$, as shown below.

Fig. 3 shows the normalized THz output power as a function of $C_{MIM}$. Rectangles are the result of the structure in Fig. 1. The oscillation frequency was $\sim 700$ GHz. Circles and the upper axis are related to the improved structure discussed later. For the rectangles, the output power significantly decreases with decreasing $C_{MIM}$ : 1/10 with the reduction in $C_{MIM}$ from 5 to 0.2 pF. The leakage of output power through the MIM layers was too small to explain this result, because the impedance of $C_{MIM}$ is low enough for the oscillation frequency. This was confirmed by a three-dimensional electromagnetic simulation.
To figure out the reason for the decrease in THz output power, we discussed the admittance $Y$ viewed the right-hand side of 1 and 1’ in Fig. 2. Fig. 4 (a) shows examples of the frequency dependence of the real and imaginary parts of $Y$ ($\text{Re}[Y]$ and $\text{Im}[Y]$). $L_{\text{sup}}$ was estimated for the shape of the sheet resistance in Fig. 1 with a three-dimensional electromagnetic simulation. Two values of $C_{\text{MIM}}$ (1 and 5 pF) were assumed.

As seen in Fig. 4 (a), $\text{Re}[Y]$ is positive in low-frequency region due to $R_{\text{sup}}$, while it is negative in high-frequency region because $L_{\text{sup}}$ suppresses the effect of $R_{\text{sup}}$. Although $\text{Re}[Y]$ is independent of $C_{\text{MIM}}$, $\text{Im}[Y]$ changes with $C_{\text{MIM}}$. If $C_{\text{MIM}}$ is large, $\text{Im}[Y]$ does not have any resonance points (i.e., zero points of $\text{Im}[Y]$) in the unstable region ($\text{Re}[Y] < 0$), as shown by the dashed curve. This means that the voltage across $Y$ is stable. However, if $C_{\text{MIM}}$ is small, $\text{Im}[Y]$ has a resonance point in the unstable region, as shown by the solid curve. A parasitic oscillation can easily occur with the frequency at the resonance point in this case, if $-\text{Re}[Y]$ compensates the conductance in the left-hand side of 1-1’ in Fig. 2.

Fig.5 shows an example of the measured oscillation spectrum for an RTD oscillator with a small capacitance ($C_{\text{MIM}} = 0.2$ pF). Several peaks at a few tens GHz and side bands around the weakened oscillation at 560 GHz were observed, which indicates the validity of the above discussion.

The decrease in the THz output power shown in Fig. 3 is explained from the parasitic oscillation as follows. Fig. 6 schematically shows the decrease in THz output power under the parasitic oscillation. Fig. 6 (a) is the current-voltage characteristics, and Fig. 6 (b) is the THz output power as a function of bias voltage. The bias voltage is assumed to be set at that for the maximum output power, $V_0$, which is nearly equal to the center of the negative differential conductance region. If the parasitic oscillation takes place, the bias voltage and the output power are modulated around $V_0$, and thus, the average of THz power decreases, as shown in
Fig. 6 (b). With decreasing CMIM, the resonance point (Im[Y] = 0) shifts toward high frequency, and −Re[Y] increases, as shown in Fig. 4(a). This results in the increase in the amplitude of the parasitic oscillation in Fig. 6 (b), and the average of THz power decreases, explaining the results in Fig. 3.

The resonance frequency of the parasitic oscillation at Im[Y] = 0 is given by $(1/2\pi)[1/(L_{cusp}C_{MIM}) - R_{cusp}^2/L_{cusp}^2]^{1/2}$, and Re[Y] at this frequency is given by $C_{MIM}R_{cusp}/L_{cusp} - G_{RTD}$. These equations imply that, by reducing $L_{cusp}$, the resonance point can be eliminated, or Re[Y] can be kept positive at the resonance point, even
if $C_{MIM}$ is reduced for high-frequency modulation. Fig. 4 (b) shows the results of $\text{Re}[Y]$ and $\text{Im}[Y]$ obtained by changing $L_{sup}$ from 200 pH used in Fig. 4 (a) to 7 pH for $C_{MIM} = 1 \text{pF}$. Although $C_{MIM}$ is small, no resonance point exists and $\text{Re}[Y]$ is positive in a wide range. To reduce $L_{sup}$, an improved structure is proposed below, in which the length of the sheet resistance is largely reduced.

### 3 Structure of RTD oscillator for high-frequency modulation

Fig. 7 shows the structure of the RTD oscillator proposed for high-frequency modulation. In contrast to the structure in Fig. 1, the MIM layers are not used at both ends of the slot antenna. As shown in Fig. 7 (b) for the central part, the upper electrode of the RTD steps over the electrode of the slot antenna as a part of an MIM layer, and the downside of the RTD is connected to the other side of the slot antenna. By this structure, the RTD and slot antenna are connected for THz waves, while the DC bias separation is achieved. As shown in Figs. 7 (b) and (c), a sheet resistance with a heavily doped ($5 \times 10^{19} \text{cm}^{-3}$) InGaAs layer is formed between the upper electrode of the RTD and the electrode of the slot antenna. The size of this resistance is $5 \mu m$ (width) $\times$ $5 \mu m$ (length) $\times$ $0.3 \mu m$ (thickness). This part plays the same role as that of the bismuth sheet resistance in Fig. 1.

![Diagram of RTD oscillator structure](image)

**Fig. 7.** Novel structure of RTD oscillator for high-frequency modulation. (a) Overall view, (b) magnification of the central part, and (c) cross section along the dotted line in (a).

An external circuit for direct modulation is also shown in Fig. 7 (a), and the equivalent circuit shown in Fig. 2 can be applied again. In the present structure, $C_{MIM}$ is formed by the MIM layer at the central part in Fig. 7 (b). $L_{sup}$ and $R_{sup}$ are formed by the InGaAs sheet resistance. Because the length of the resistance is much smaller than that of the previous bismuth case, $L_{sup}$ is much reduced (7 pH) compared with that in the previous case (200 pH). The fabrication process was also simplified by the use of semiconductor layer for the resistance.

Measured results of the THz output power as a function of $C_{MIM}$ are shown by
circles in Fig. 3. The oscillation frequency was ~350 GHz, which was lower than that of the previous structure because of the difference in RTD area and antenna length. However, this difference has little influence on the results in Fig. 3, because the impedance of $C_{MIM}$ is still low enough for the oscillation frequency. As seen in Fig. 3, the THz output power in the improved structure was almost constant against the reduction in $C_{MIM}$, in contrast to the results for the previous structure shown by rectangles. We speculate that this result is attributed to the suppression of parasitic oscillations by significant reduction in $L_{app}$, as discussed in Fig. 4 (b).

On the upper axis of Fig. 3, the 3-dB cut-off frequency of modulation is also shown for the improved structure. This frequency is defined as that at which the squared voltage across 1-1’ in Fig. 2 equals to 1/2 of that at low frequency limit, and was estimated from each value of $C_{MIM}$ on the lower axis of Fig. 3 with the equivalent circuit in Fig. 2. $L_{wire}$ was neglected in this estimation. The above definition of the 3-dB cut-off frequency corresponds to that for the power of the demodulated signal at the receiver. From the upper and lower axes of Fig. 3, a modulation frequency of more than 10 GHz is expected for $C_{MIM}$ less than ~0.8 pF without degradation in THz output power.

### 4 Modulation characteristics

Frequency response of the direct intensity modulation was measured for the oscillator with the improved structure shown in Fig. 7. The measurement setup is shown in Fig. 8. A modulation signal superimposed on the bias voltage is fed into the RTD oscillator from the port 1 of the vector network analyzer (VNA). The modulated THz wave radiated from the RTD oscillator is reflected by two off-axis paraboloidal mirrors, and focused on a Schottky barrier diode (SBD) detector with a horn antenna. The horn antenna at the detector side is convenient to block out the direct incidence of the modulation signal into SBD, because the modulation frequency is lower than the cut-off of the horn and waveguide. The demodulated signal from the SBD detector is put into the port 2 of the VNA. The bandwidth of the SBD is at least 40 GHz. The modulation characteristics were obtained from the $S_{21}$ parameter measured by the VNA.

![Fig. 8. Measurement setup for the modulation characteristics of RTD oscillators.](image)
The RTD oscillator with the oscillation frequency of 350 GHz was mounted on a silicon hemispherical lens for extraction of output power. To apply the modulation signal and DC bias, the electrodes of the oscillator were connected to a microstrip line with gold bonding wires [6]. Fig. 9 shows the bias dependence of the normalized output power. The horizontal axis is the bias voltage of the RTD applied through the VNA, which is higher than the actual voltage applied to the RTD because of the voltage drop in bias circuits. The bias voltage was set at 1.48V in the modulation experiment, as shown by a circle in Fig. 9. The power received by the SBD detector was a few microwatts. The amplitude of the modulation voltage was adjusted so that the modulation amplitude in output power was maximized at low frequency. The modulation power output from the port 1 was around -10 dBm in this condition.

![Normalized output power of RTD oscillator as a function of bias voltage. Bias point in the modulation experiment is also shown.](image)

**Fig. 9.** Normalized output power of RTD oscillator as a function of bias voltage. Bias point in the modulation experiment is also shown.

![Frequency response of direct intensity modulation measured for the RTD oscillator with the structure shown in Fig.5.](image)

**Fig. 10.** Frequency response of direct intensity modulation measured for the RTD oscillator with the structure shown in Fig.5.
Fig. 10 shows the measured result of $S_{21}$, which is expressed as the power ratio of the demodulated signal fed into the port 2 to the modulation signal output from the port 1, for the RTD oscillator with $C_{\text{MIM}}$ of 0.7 pF. A 3-dB cut-off frequency of ~30 GHz was achieved. The cut-off frequency estimated from the equivalent circuit in Fig. 2 was ~10 GHz, as indicated on the upper axis of Fig. 3. A cut-off frequency higher than this estimation was obtained in the experiment. This is probably because of the peaking due to a parasitic inductance connected in series with the RTD, such as that of the bonding wires, although a detailed discussion with a more exact equivalent circuit for the actual structure is a future subject.

A higher cut-off frequency is expected with further reduction in MIM capacitance. Although the output power in the present device is not enough to obtain a sufficient signal-to-noise ratio for high-speed data transmission experiments, a high output power is possible by the optimization of the antenna structure [16]. The structure for high-frequency modulation proposed in this paper is applicable to RTD oscillators with higher oscillation frequency obtained by the improvement of RTD and antenna structures [13, 14, 15].

5 Conclusions
We proposed and fabricated RTD THz oscillators with a structure for high-frequency modulation, which is useful for high-capacity terahertz communications. The capacitance of the MIM layers forming the slot antenna is the dominant element limiting the modulation frequency, and the cut-off frequency of modulation can be increased by reducing this capacitance. However, the previous structure had a problem that the output power decreases with the decrease in this capacitance. Using an equivalent circuit model, we figured out the mechanism of the degradation in output power for the oscillators with small MIM capacitance. Based on this result, a novel structure was proposed for high-frequency modulation. THz oscillation without degradation in output power was obtained in this structure even with a small MIM capacitance. A high cut-off frequency of 30 GHz was obtained in the direct intensity modulation of the device oscillating at 350 GHz with the reduced MIM capacitance of 0.7 pF. A higher cut-off frequency is expected with further reduction in MIM capacitance.

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