Possibility of THz detection with resonant tunneling super regenerative detectors based on extremely high order harmonics

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Abstract: A super regenerative detector employing a resonant tunneling diode (RTD) was investigated for THz wave detection. A key is to use extremely high order harmonics of the fundamental oscillation of the regenerative oscillator. This has various advantages, such as circuit simplicity, easy design, and low power consumption. The basic operation and the possibility of the THz wave detection were demonstrated by circuit simulation.

Keywords: resonant tunneling, super regenerative detector, THz, oscillator, negative differential resistance

Classification: Electron devices, circuits, and systems

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1 Introduction

A resonant tunneling diode (RTD) is one of the most promising THz devices. Oscillators based on negative differential resistance is a most straightforward application of the RTDs. Fundamental oscillations over 1 THz have already been demonstrated in recent years [1, 2, 3]. Detectors based on strong non-linearity of the RTD is also a promising application [4]. 300 GHz wave transmission has been demonstrated using an RTD detector [5], and an ultrashort time sampling using RTDs have been proposed recently [6].

In the THz frequency range, it is difficult to amplify signals. Therefore, high sensitivity is one of the most important factors for the THz detectors. Super regenerative detectors based on oscillators have been known to have very high sensitivity since their invention [7]. Recently, super regenerative detectors have been gaining increasing interests for micro and millimeter wave applications. Employing RTDs for super regenerative detectors is promising for ultra high frequency operation. Super regenerative detectors operating at 60 GHz has been recently reported employing the gated RTD device [8].

In this paper, we propose a novel super regenerative detector employing an RTD for THz signal detection. A key to this is to use extremely high order harmonics. We demonstrated the basic operation and discussed the performance in the THz signal range based on circuit simulation.

2 Circuit configuration and basic operation

Figure 1 shows the basic configuration of the super regenerative detector we investigated. It consists of an RTD oscillator with an input port, and a bias (clock) supplying circuit. The RTD oscillator consists of an RTD, an inductor L_R , and a bias capacitor C_b . Input signal is fed into the circuit via the input capacitor C_{IN} . If we model the RTD as a parallel circuit of a current source $I_{RTD}(V)$, and a capacitor C_{RTD} , the free-running oscillation frequency is approximated as,

$$f_0 = \frac{1}{2\pi\sqrt{L_{osc}(C_{RTD} + C_{IN})}}, \quad (1)$$

since the bias capacitance, C_b , is set to be much larger than C_{RTD} . (Here, we assume that the input signal is supplied from a voltage source.)

Fig. 1. Basic circuit configuration of the super regenerative detector using an RTD.

Fig. 2. Waveforms of the RTD super regenerative detector shown in Fig. 1 obtained from circuit simulation. The parameters used were shown in Table I. (a) Bias (clock) voltage, V_{Pulse} , (b) V_{RTD} without input signal, (c) V_{RTD} with input signal (14 GHz, 0.1 V_{pp}).

Table I. Circuit parameters used in simulation.

RTD peak current	5 mA	L_R	1 nH
RTD capacitance	10 fF	C_{IN}	0.1 pF
RTD peak voltage	0.35 V	C_b	10 pF
RTD series resistance	2 Ω	L_b	10 nH
V_a	1.0 V	R_b	50 Ω
V_b	0.6 V	f_0	~ 14 GHz

To operate the circuit in the super regenerative mode a periodic bias voltage, as shown in Fig. 2 (a) for example, is applied to the bias node. We chose the V_a to bias the RTD in a upper positive differential resistance (PDR) region, while the V_b is to bias the RTD in the negative differential resistance (NDR) region. The oscillation stops when the bias voltage is V_a , while the oscillation begins when the bias voltage is V_b . We chose the upper PDR region instead of lower PDR region for stopping the oscillation, because it is advantageous for avoiding the effects of hysteresis in the current-voltage curve.

We will explain the basic operation of the circuit based on the simulation results shown in Fig. 2. The simulation was carried out with the parameters shown in Table I. The voltage dependent current source of the RTD, $I_{\text{RTD}}(V)$, is the same as shown in [9] with the RTD area of $5 \mu\text{m}^2$. The time variation of the bias voltage, V_{Pulse} , and the voltage applying to the

Fig. 3. Waveforms of the RTD super regenerative detector for harmonic inputs. (a) 28 GHz, (b) 56 GHz, (c) 896 GHz. The signal amplitude is fixed to be $0.1 V_{pp}$. Black arrows show the time when oscillation begins if there is no input signal.

RTD, V_{RTD} , are shown in Fig. 2 (a) and (b), respectively. The period of the bias voltage is 5 ns. As shown in the figure, oscillation with a frequency of $f_0 \sim 14$ GHz begins at a certain time, t_s , after the bias voltage falls down to V_b . When the sinusoidal input signal at frequency of f_0 is fed to the circuit, the oscillation begins earlier as shown in the Fig. 2 (c). The oscillation start time, t_s varies depending on the input signal amplitude. Therefore, one can determine the input signal amplitude by measuring the t_s . This can be done with envelope detection circuit connecting to the node N1. If it is connected via FET buffer, it has nearly no influence on the circuit operation because the C_b is much larger than $C_{RTD} + C_{IN}$.

3 Operation for harmonic inputs

In this section, we discuss the circuit operation of the RTD super regenerative detector for harmonic inputs. It has been reported that the super regenerative circuit can detect second harmonic signals [10]. A most significant point in our proposal is to apply this detector to extremely high order harmonic signals. Owing to the high frequency operation of the RTD, the RTD super regenerative detector can operate for harmonic signals in a THz range.

Fig. 3 shows the waveforms of V_{RTD} for the sinusoidal input of 28, 56, and 896 GHz, respectively. The signal amplitude is fixed at $0.1 V_{pp}$. The t_s for no input is shown in the figure by an arrow for reference. As shown in the Fig. 3 (a), the difference in the oscillation start time, $t_{s0} - t_s$, where t_{s0} indicates the t_s for no input, reduces drastically from 2.08 ns for the fundamental

Fig. 4. Input signal frequency dependence of the oscillation start time difference, $t_{s0} - t_s$, for various signal amplitudes. Continuous oscillations were observed for $0.2 V_{pp}$ at 14 GHz, $0.4 V_{pp}$ at 14 and 28 GHz. This implies the time difference is larger than 5 ns for these conditions.

frequency input to 0.29 ns for second harmonic input. However, we found that this value scarcely changes when we increase the order of harmonic further. Figure 3 (b) shows the V_{RTD} for 56 GHz input, which is very close to that for 28 GHz input, and $t_{s0} - t_s$ is 0.26 ns. A most striking feature is that it remains almost constant even if we increase the input frequency to a THz frequency range. No significant difference can be observed for the 896 GHz input shown in Fig. 3 (c).

We plotted the oscillation start time difference, $t_{s0} - t_s$, as a function of the input signal frequency in Fig. 4 for various signal amplitudes. As shown in the figure, the $t_{s0} - t_s$, decreases rapidly when the input frequency changes from the fundamental frequency to the second harmonic frequency. However, it remains almost constant for the harmonics even in the THz frequency range. It should be noted that the oscillation frequency is unchanged and remains at about f_0 even for THz inputs. This low frequency oscillation permits us to detect t_s easily by the same circuit mentioned in the previous section. These results demonstrate the promise of the RTD super regenerative detector for THz signal detection.

4 Conclusion

We have proposed the super regenerative detector using an RTD. Basic operation for the fundamental frequency input signal was verified by circuit simulation. Moreover, possibility of the circuit operation was investigated for harmonic inputs. It is demonstrated by circuit simulation that the extremely high order harmonics, which are in the THz frequency range, can be detected

by this circuit. This super regenerative detector is promising for THz signal detection.

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