Large-amplitude voltage edge oscillating in a transmission line with regularly spaced series-connected resonant-tunneling diodes

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Abstract: We investigate the increased amplitude of oscillating pulse edge developed in a transmission line periodically loaded with series-connected resonant-tunneling diodes (RTDs). In general, the series-connected RTDs in the middle part of the line can be stabilized in one of the multi-stable states that may disable the proper edge oscillation. We find that it becomes possible to design the line to support such a simple oscillating edge by managing the time required for the state transition of bistable states and the oscillation amplitude increases in proportion to the number of series-connected RTDs through SPICE calculations.

Keywords: synchronization, oscillation, resonant-tunneling diodes, series-connected devices

Classification: Microwave and millimeter-wave devices, circuits, and modules

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1 Introduction

Resonant tunneling diodes (RTDs) have been recognized as being advantageous for high-frequency signal generation including terahertz bands [1, 2, 3]. However, the relatively narrow voltage range exhibiting negative differential resistance (NDR) limits the oscillation amplitude of RTD-based oscillators [4]. It has been shown that the introduction of series-connected RTDs in place of a unique RTD may contribute to the increased oscillation amplitude by short-pulse or continuous-wave excitations [5, 6, 7]. In general, the DC operating points in NDR regions of the circuit using series-connected RTDs are unstable [6]. Some of them are biased at the positive differential resistance (PDR) region existing at lower voltages than the NDR one, while the others are biased in another PDR region present in greater voltages than the NDR one. In ordinary RTD oscillators, every series-connected RTD must be biased at the voltage in its NDR range that is recovered through the application of either the short pulse or continuous wave. Because of the RTDs are connected in series, each device exhibits a common temporal variation of current/voltage; therefore, the terminal oscillatory voltage of each RTD additively contributes to the oscillation amplitude. On the other hand, it is observed that a voltage edge repeatedly turns around halfway on an RTD line when one of the ends is applied by an appropriate DC voltage [8], by which a voltage edge develops and moves to the far end. The edge is gradually attenuated by the electrode loss and/or substrate leakage; it nearly disappears. At this stage, a stable traveling front develops and starts propagating back to the near end. The voltage edge repeats this process via the reflection at the near end, thus oscillating on the line. In this study, we replace a unique RTD in each cell of the line with series-connected multiple RTDs to expect the increased amplitude of the oscillating edge. After discussing the method to suppress the development of bistable states in the line, we characterize the device by using SPICE calculations.

2 Fundamental properties of investigating RTD line

Fig. 1 shows the line structure. Two cells, which are composed of the line inductance $L$, line resistance $R$, line capacitance $C$, and series-connected RTDs, are shown. Here, we illustrate $n$ series-connected RTDs. An RTD is modeled by
parallel connection of a parasitic capacitance $C_{RTD}$ and a nonlinear current source $I_{RTD}$, which is based on Schulman’s model [9].

Consider the case where two RTDs are connected in series and biased with a single DC voltage source to be in the NDR region. Then, three different states of bias-voltage distribution are possible. First, both RTDs are biased at a common voltage in the NDR region. On the other hand, both RTDs are biased in the PDR region, one at a voltage lower than the peak voltage, and the other at a voltage higher than the valley voltage. In the latter case, which RTD to be biased in the lower PDR renders two different states. It is well-known that the first state is unstable when there is no time-variant signal present in the circuit, and the RTD state transfers toward one of the latter two. This property influences the dynamics of oscillating edge in an RTD line. The spatial voltage waveform in Fig. 2(a), obtained by the SPICE calculation for a model RTD line, shows the snapshot of the back-and-forth line voltage recorded at the returning phase. The whole transient range tends to return to the first cell as the green arrow designates. Two series-connected RTDs are loaded in each cell and the total cell size is 50. As discussed in the following, the bi-stability of the series-connected RTDs influences the dynamics of oscillating edge(s) significantly. In general, either the finite noisy currents/voltages or fluctuation of device parameter values may resolve which stable DC point to be settled in. Presently, all the parameter values are fluctuated with ±5% standard deviation and no noisy current/voltage sources are assumed. The average values of $L$, $C$, and $R$ are set to 2.0 nH, 1.0 pF, and 0.2 Ω, respectively. In addition, the average RTD peak current density and per-unit-area parasitic capacitance are set to $10^5$ A/cm$^2$ and 2 fF/µm$^2$, respectively. The RTD area is set to 30 µm$^2$. In Fig. 2(a), the terminal voltages of the upper and lower RTDs are represented by $V_u$ (red) and $V_l$ (blue), respectively. The first cell is biased at 1.8 V. Owing to $R$ and $I_{RTD}$, the line voltage $V_t$, defined by $V_u + V_l$, decreases as the cell address increases. In the neighborhood of the first cell, $V_t$ is sufficiently large that the operating point of the series-connected RTDs is uniquely defined as illustrated in (A), where $V_t$ is almost twice as large as $V_{u(l)}$ exhibiting large-amplitude voltage swing. That operating point is also unique for the cells far from the first cell as in (C), although $V_t$ becomes less than the peak voltage of RTDs. In the cells between these two extreme ranges, the RTDs exhibit bi-stability as illustrated in (B). Because of the parameter-value fluctuations, which of $V_{u,l}$ becomes greater depends on the cell address. The presence of this spatial range makes the dynamics of the oscillating edge complicated. In the present case, that range oscillates in one body while changing its shape. Notice that $V_t$ becomes similar to that observed in a single-RTD line.

**Fig. 1.** Structure of transmission line with regularly spaced series-connected RTDs.
One of the method to obtain a simple large-amplitude edge oscillation is to increase $C_{RTD}$ up to the same order as $C$. Because the response time required for switching from the unstable to stable DC points in bistable states is roughly estimated by the $C_{RTD}\Delta V_i/\Delta I_{peak}$, where $\Delta V_i$ and $\Delta I_{peak}$ define the amplitude of voltage edge and the difference in peak currents of series-connected RTDs, respectively, it becomes possible for the DC point of the cells originally exhibiting bi-stability to be kept at the NDR region by the sufficient increase in $C_{RTD}$, such that the state-transition time to become greater than the time for the edge to pass through the corresponding cell. In order to examine the impact of this arrangement, we increase the average value of $C_{RTD}$ to be the same as that of $C$ (1.0 pF), while the other average parameter values and standard deviation of fluctuation are unaltered.

In order to make the location of the bistable cells relatively far from the first cell, the bias voltage is a little bit increased to be 1.9 V. The SPICE calculation results in Fig. 2(b). As expected, the cells exhibiting bi-stability range farther from the first cell than those in Fig. 2(a). Moreover, that bistable waves are not dragged by the returning edge attached by the green arrow, and stay at the original positions and disappear eventually. A simple and nearly identical edge is observed to oscillate for both $V_u$ and $V_l$, resulting in the development of oscillating edge whose amplitude becomes twice as large as that in a single-RTD line.

Similar dynamical behavior is expected in the line with three or more series-connected RTDs, when the bias voltage is appropriately applied, such that the number of lower-PDR RTDs in the static state becomes coincident with that of upper-PDR ones. In that case, the increase in $C_{RTD}$ contributes to the slow state-transition in a pair of lower- and upper-PDR RTDs, and the corresponding RTDs succeed in keeping biased at their NDR voltage. For odd $n$, the bias voltage must be set for the azygous RTD to be biased in the NDR range.

![Fig. 2. Properties of oscillating voltage edge in a line having two series-connected RTDs in each cell. $C_{RTD}$ is set to (a) 2 fF and (b) 1 pF, respectively.](image)
3 Numerical results

We demonstrate the large-amplitude oscillating edge in a line with series-connected RTDs in each cell. Assuming the 1.0 µm-order inter-cell lengths, the average values of $L$, $C$, and $R$ are set to 1.5 pH, 0.5 fF, and 0.65 Ω, respectively. In reference to the performance of the state-of-the-art RTDs [10], we set the RTD current density and area to 2.0 MA/cm² and 2 µm², respectively. The total cell size, the standard deviation of fluctuation, and average RTD peak current density are the same as those used to obtain Fig. 2. Fig. 3 shows the spatiotemporal voltage profiles observed in the line with $n = 2, \cdots, 5$. Each figure is measured by the common scales, although the axes labels are shown only for Fig. 3(b) for clarity. The bias voltage is set to 2.0, 3.2, 4.9, and 6.2 V for $n = 2, 3, 4, \text{ and } 5$, respectively. The profile similar to a saw blade corresponds to the development of the back-and-forth oscillating edge. In addition, the increased amplitude of that edge with $n$ is successfully observed. In a single-RTD line, the edge oscillation develops for wide range of bias voltage. In contrast, the bias voltage is allowed only in rather restricted range for multiple-RTD line, because it must guarantee the balance between the lower- and upper-PDR-RTD numbers, and the majority of RTDs positions in the lower (upper) PDR range for small (high) bias voltages. The lower and upper limits $V_{bL/bU}$ and $\Delta V_b (\equiv V_{bU} - V_{bL})$ of the bias voltage range for developing an oscillating edge are listed in Table I. As expected, $\Delta V_b$ is very small and tends to be reduced further for odd RTDs because of the lack of complete pairing of the lower- and upper-PDR RTDs. On the other hand, Fig. 4(a) shows the emitter voltage recorded at the 15th cell of each series-connected RTD for the five-RTD line. The waveform color represents which RTD to be recorded. For example, the red waveform shows the emitter voltage of the uppermost RTD. Each terminal voltage exhibits almost common variation and contributes additively to the formation of large-amplitude periodic signal. The line voltage monitored at the 11th cell is shown in Fig. 4(b). We can see that the oscillation amplitude almost
proportionally increases as $n$ increases. In contrast, the current flowing in the series-connected RTDs has little dependence on $n$, because each RTD is biased at the line voltage divided by $n$; therefore, the turn-around point of the oscillating edge shifts to the far end as $n$ increases as observed in Fig. 3. This results in the decrease in oscillation frequency with $n$. Actually, the oscillation frequency is calculated to be 443.5 and 284.9 GHz for $n = 2$ and 5, respectively. The decrease in frequency is no more than 64%.

### 4 Conclusion

With proper managements of bistable states of series-connected RTDs, an RTD line can support large-amplitude oscillating voltage edge. The increase in RTD capacitance is really effective. Although our circuit has the drawback that the oscillation frequency decreases with amplitude increase, the amplitude increases in proportion to the number of series-connected RTDs.

| $n$ | $V_{bL}$ (V) | $V_{bU}$ (V) | $\Delta V_b$ (V) | $n$ | $V_{bL}$ (V) | $V_{bU}$ (V) | $\Delta V_b$ (V) |
|-----|--------------|--------------|-----------------|-----|--------------|--------------|-----------------|
| 2   | 1.96         | 2.68         | 0.72            | 4   | 4.71         | 4.93         | 0.22            |
| 3   | 3.20         | 3.20         | 0.00            | 5   | 5.87         | 5.91         | 0.04            |

**Fig. 4.** Temporal waveforms in the line. (a) The emitter voltages of 5-RTD line at the 15th cell and (b) the typical waveforms of $n$-RTD line (black: $n = 2$, blue: 3, green: 4, and red: 5) monitored at the 11th cells.