Simulation of a Subharmonic Excitation of Series Integrated Resonant Tunneling Diodes

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***Abstract*— A subharmonic pulse excitation of an oscillator of series-integrated RTD's is considered and simulated. Linearized considerations are used to analyze the nonlinear system dominated by two major frequencies. A voltage-dependent current source is adopted to separate the input and output power for convenient simulation. Simulations show, for example, a 100-GHz integrated RTD oscillator can be excited by a 50-GHz pulse with 1-ns decay time without the dc instability problem, while a voltage ramp of 1-ns rise or fill time is far too slow to initiate such an oscillator.**

I. Introduction

MORE THAN 700 GHz [1] of oscillation has been demonstrated by using a single Quantum-Well Resonant Tunneling Diode (RTD) [2], [3]. It is the solid state oscillator with the highest frequency. However, the reported power has been very low, often a few mWatts [1]–[3]. Therefore, the integration of RTD's for substantially more power generation is essential for many useful applications [4]. In this letter, we report a successful simulation of a proposed subharmonic excitation of a oscillator with series-integrated RTD's. The implication is that implemented with a quasi-optical multiplier type of circuit [5], useful power well into millimeter and submillimeter waves can be generated by integrated RTD's.

II. Theoretical Consideration

The small reported power of a single RTD oscillator is mainly due to its low device impedance [2]. Therefore, series integration of RTD's is a very desirable start for power enhancement. Due to the severe ohmic loss even for metal at millimeter- and submillimeter-wave frequency, device-level integration is very important. It often provides a solid foundation for further circuit-level integration.

A well-known dc instability problem poses a difficulty for series integration of any negative resistance diode exhibiting dc Negative Differential Resistance (NDR) [6]. RTD's, like tunnel diodes, have their NDR from dc I-V characteristics. One way to circumvent this difficulty was proposed and demonstrated experimentally by Vorontsov and Polyakov [6]. A voltage shock wave was applied to 10 tunnel diodes to drive the bias voltage of every diode into the NDR region to initiate oscillation. The oscillation is stabilized by designing a resonant circuit to give a large RF voltage amplitude [6]. To apply to RTD's at much higher frequency, very fast voltage ramp is required [4].

In this work, we consider the possibility of exciting the series integrated RTD oscillator by a RF pulse at subharmonic frequency. There are many solid state sources at the lower end of millimeter-wave frequencies. The proposed scheme can therefore be implemented more easily than the use of a voltage ramp.

To our knowledge, no such subharmonic excitation has been reported. The following theoretical arguments support such a possibility. First of all, it seems always possible to drive the series connected RTD's into the NDR region, even with lower-frequency RF source as long as the amplitude is sufficiently large by either one of the following two mechanisms: The first is that if the amplitude is sufficiently large and the frequency is not too low, the capacitive current of each RTD can be made dominant over the conductive current. The second mechanism is the RF instability shown in the rectified I-V curve [7]. Once this happens, all the RTD's are forced to share almost equally the total voltage. If the total voltage is properly adjusted, all the RTD's can be driven into the NDR region. If in this situation the RF excitation source is turned off, it is possible that all the RTD's will oscillate at the frequency determined by the oscillator circuit, which is twice or more of the excitation frequency. A simplified analysis can show this possibility. In Fig. 1(a), we show a schematic diagram of a simplest circuit for such purpose. Note that to optimize subharmonic excitation, a multiplier-type of circuit can be used to enhance the efficiency, which we have not done here. Note also that when quasi-optical circuits are used, input and output are separated without the requirement of a circulator as in a frequency multiplier [5]. If we treat the total conductance $-G_n$ of the series integrated RTD as a time-dependent function, then the circuit behavior can be predicted if the $-G_n$ function is given. We have analyzed the problem when the input frequency is close to the oscillator frequency and found that this can indeed be done [8]. Now with subharmonic excitation, the techniques we developed in [8] cannot be applied. However, we may view the problem in this way. Initially, $-G_n$ is positive, i.e. dissipative, because the individual RTD's are in PDR region. The subharmonic excitation drives the RTD's into NDR regime and $-G_n$ becomes negative, i.e. generative, even at fundamental frequency. This $-G_n$ will amplify the fundamental frequency, which first appears as a harmonic component for the subharmonic excitation. When the subharmonic excitation pulse begins to decay, the $-G_n$

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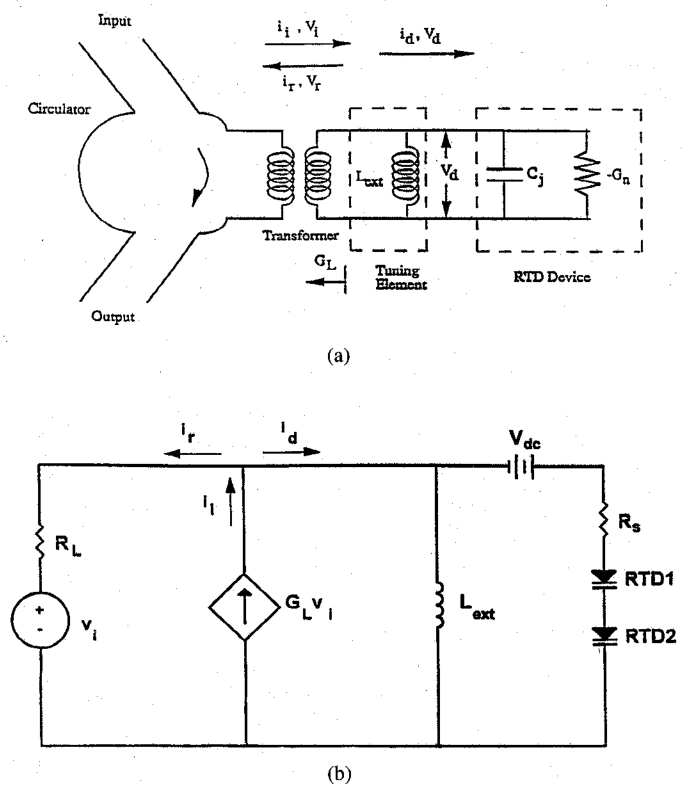

Fig. 1. (a) A schematic circuit diagram for subharmonic pulse excitation of an oscillator of series integrated RTD's. (b) A convenient equivalent circuit model to separate input and output power of the integrated oscillator circuit of Fig. 1(a).

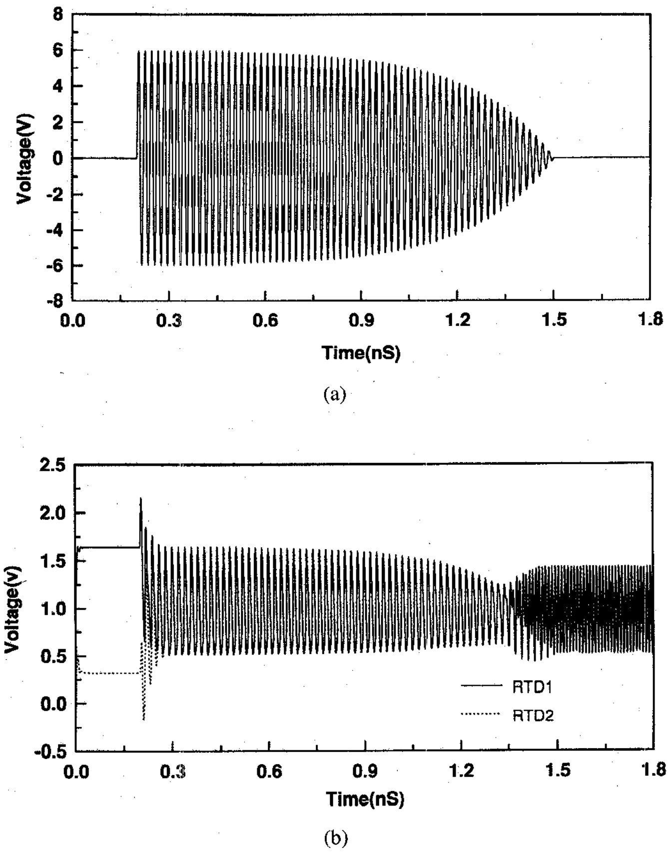

Fig. 2. (a) A 50-GHz input voltage pulse used in our simulation. (b) The corresponding two voltages across each of two RTD's, driving into NDR region at the beginning of the input pulse, changing from 50 to 100 GHz near the end of the input pulse.

may further increase because the initiate RF amplitude can be made larger than that of the maximum $-G_n$. Thus, while the subharmonic excitation pulse dies down, the fundamental has a chance to quickly shoot up and maintain its oscillation.

Such a linearized picture is well-known in multiple periodic nonlinear system [9]. The effective conductance for each harmonic of a two-frequency dominant system can be obtained by a double Fourier integral [9]. While we will work out an analytic theory for their problem, we first report in the following the successful computer simulation of the subharmonic excitation scheme.

III. Simulation and Result

SPICE is used in our simulation of Fig. 1. The first crucial point here is how to separate the input and output in the simulation. Even with the modified version of Microwave SPICE, an element such as a circulator is not available. This is understandable, since SPICE was originally designed for integrated circuits, not microwave circuits. We have overcome this difficulty by adopting a clever dependent current source. Fig. 1(b) is the equivalent circuit model that we choose to represent Fig. 1(a) in SPICE. The input voltage is represented by an independent voltage source that is in series with the load resistance R_L. Note that the R_L is the reciprocal of the G_L of Fig. 1(a). The dependent current source $G_L V_i$ gives the input current i_i in Fig. 1(a). The reflected current i_r in Fig. 1(a) is represented by the branch current of the branch with the V_i source. It is then straightforward to show that the device current i_d and voltage V_d in Fig. 1(b) relates the input and output currents and voltages in exactly the same fashion as in Fig. 1(a).

Two RTD's are used here to demonstrate the scheme. We have adopted the experimental RTD I-V curve of [10] in our simulation. The maximum $-G_n$ is found to be about 3.6 mS. A constant capacitance is used for each RTD with value from [10]. It is a good approximation even for large RF voltage [11]. Through simulations, we find that there are various situations that it is indeed possible to excite and maintain the oscillation by subharmonic pulse. For example, we report in the following the case of the input voltage of a 50-GHz pulse with a 6-V amplitude. The pulse starts at 0.2 ns abruptly and begins to decay from 0.5 ns. It decays to zero at 1.5 ns with a characteristic time of 0.2 ns, as shown in Fig. 2(a). When this pulse is applied to the SPICE simulation with 1 mS for the G_L, the voltage response from each of the RTD is presented in Fig. 2(b), and the resultant voltage from 1 ns to 1.6 ns across the two integrated RTD's is shown in Fig. 3. In Fig. 2(b), the fast driving of the two RTD's into the NDR region after about 0.1 ns of the pulse can be seen. It is clear from Figs. 2 and 3 that after 1.5 ns, the input essentially dies out, yet the oscillator maintains an oscillation at about 100 GHz. The transition from 50 to 100 GHz oscillation occurs near 1.4 ns. The 100 GHz begins as a small harmonic component slightly before 1.4 ns. It then grows in a time scale of about 0.1 ns to full strength and

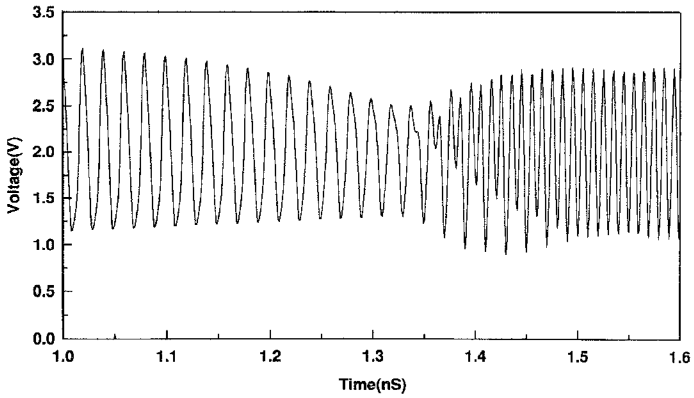

Fig. 3. The total device voltage across two RTD's of the 100-GHz oscillator after the subharmonic 50-GHz pulse excitation.

dominates the oscillation. The substantial growth of the 100-GHz oscillation begins around 1.35 ns in Fig. 3, where the RF voltage amplitude for each RTD is about 0.25 V. We find that 0.5 V is the range of the NDR region of the experimental I-V curve [10]. Therefore, the effective negative resistance $-G_n$ grows to a maximum when the input RF pulse is decayed to about 2.5 V, which corresponds to the RF amplitude of 0.25 V across each RTD at 1.35 ns. Transit time effects for $-G_n$ that are neglected here should be included as discussed in [4] for much higher frequencies.

It is important to find that 1-ns decay time in the subharmonic pulse is able to excite and maintain a 100-GHz integrated RTD oscillator. It is impossible for a 1-ns voltage ramp to do the same thing [4]. The reason is that for a subharmonic excitation, the 100-GHz harmonic is already there during the 50-GHz pulse and quickly builds up in about 0.1 ns when the pulse decays. On the other hand, in a voltage ramp excitation, the 100 GHz must build up from noise for the whole 1-ns period, which is too long to prevent switching of the bias of each RTD [4]. In fact, 1-ns voltage ramp is far too slow for such an excitation [4]. This is an important advantage of subharmonic excitation.

Simulations with different decay time show that the excitation cannot be successful if it decays too slowly. This is related to the well-known dc instability phenomena [4]. Note that the subharmonic triggering mechanism is different from that of the conventional injection locking [4]. Excitations at even lower frequencies are also found possible; more details will be published. A preliminary experimental demonstration using tunnel diodes has shown subharmoinc excitation [12].

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