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Study of Injection Locking Effect in Terahertz Resonant Tunneling Diode Oscillators

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***Abstract*—In this article the injection locking effect in terahertz (THz) resonant tunneling diode (RTD) oscillators is studied using a circuit simulation method. The simulation model is implemented in a popular simulator called Keysight ADS for ease of use and effective investigation. The locking phenomenon is successfully observed. Pulling range, locking range, locking conditions and influence of antenna resistance on locking range of the effect are carefully discussed. We found that locking range is wide, locking effect can be occurred at a relatively low injected power and injection locked RTD THz oscillator array is feasible.**

I. INTRODUCTION

THz wave which lies within frequency band from 0,1 THz to 10 THz [1] between microwave and infrared light regions finds a wide variety of promising applications such as spectroscopy, sensing, high resolution imaging, and wireless communications. This originates from its unique characteristics including extremely wide available bandwidth and exhibiting "finger print" to living tissues. For commercial purposes, THz sources need to provide possibility of integrity, compactness, high stability as well as low-cost but still ensuring high performance. RTD is a very promising candidate which can meet these requirements because it is not only a cost-effective but compact device. In addition, it has a very low power consumption and high oscillation frequency [2]. RTD has been used as THz transmitter and receiver for THz wireless communications [3]. Moreover, it is also used in sensing applications [3]. However one of the major issues for the present RTD is it exhibits low output power and high phase noise [4]. In microwave technologies, a popular solution to these issues is using the injection locking technique where a low output power and high phase noise oscillator is locked to an external clean source to improve both the output power and phase noise performances [5], [6]. In addition to this, when oscillators are mutually locked to each other based on this method, a coherent oscillator array can be realized [7]. The oscillator array plays a key role in various applications as it can offer high power as well as low phase noise performance. This approach can be also applied to the THz RTD oscillators but so far there has not any articles reported on this effect for the THz region. Therefore we aim to investigate this approach applied in the RTD oscillators in the present study.

The paper is organized as follow, in Sec. II a circuit model is constructed in a Keysight ADS simulator to observe the injection locking effect of the THz RTD oscillator. In Sec. III we carefully investigate the effect based on the constructed model. From the investigated results various important discussions are presented in Sec. IV. Finally, Sec. V will conclude the paper.

II. CONSTRUCTION OF THE MODEL

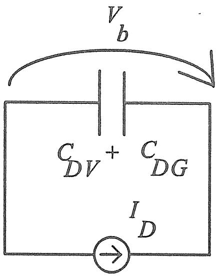

Fig. 1. Equivalent circuit of the RTD

Fig. 1 shows the equivalent circuit of the RTD. It consists of a nonlinear current which in turn is in a parallel connection with two capacitors. RTD current I_D is a function of bias voltage V_b as described by the following formula [8]

$$I_D(V_b) = -a(V_b - V_0) + b(V_b - V_0)^3 + I_0 \qquad (1)$$

where a, b, I_0, V_0 are constants.

From (1) it is clear that I-V characteristic of RTD is approximated by a third order symmetric polynomial.

RTD capacitance contains a constant capacitor C_{DG}, which is proportional to the RTD geometry, and a voltage dependant capacitor C_{DV}, which accounts for the voltage dependent characteristic. C_{DV} used in the RTD model is described as below [5]

$$C_{DV}(V_b) = \begin{cases} \tau(-a + 3b(V_b - V_0)^2), & -a + 3b(V_b - V_0)^2 < 0 \\ 0 & , -a + 3b(V_b - V_0)^2 \geq 0 \end{cases}$$

(2)

Here τ is the fitting parameter, which is used for model fitting with measurements data.

Based on this equivalent circuit and from (1) and (2), a simple RTD model is constructed in the Keysight ADS simulator.

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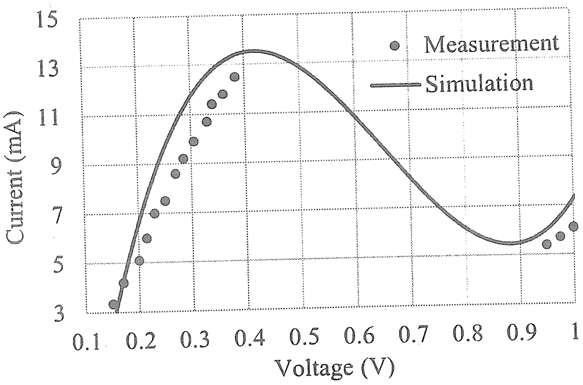


Fig. 2. Static I-V characteristic of the RTD

Fig. 2 shows the measured and simulated static I-V characteristics of the RTD. Here the extracted parameters of the RTD model are $a = 0.026$ S, $b = 0.16$ S/V^2, $I_0 = 0.0095$ A, $V_0 = 0.65$ V, $\tau = 3.2\cdot10^{-15}$ s. These parameters are extracted from a fabricated RTD with the mesa size of 1.6 μm^2. It can be clearly seen that although the RTD is described with a simple model, there is a good agreement between the model and measurement. Here the IV measurement was done using a GSG probe which is connected to the RTD pads. There is no measurement data in negative differential region due to oscillation.

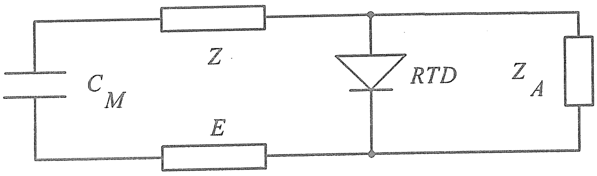


Fig. 3. RTD oscillator schematic

Based on this model, an RTD oscillator is constructed and its schematic is given in Fig. 3. The oscillator comprises a RTD, a load impedance Z_A which is the antenna impedance at the oscillation frequency and an ideal transmission line whose characteristic impedance and electrical length are Z, E respectively. It is terminated by a large capacitor C_M. Here the antenna can be a dipole, bowtie or slot line. Since the transmission line is shorted by C_M capacitor, it acts as an inductor whose value is determined by the electrical length of the transmission line. The oscillation takes place if the absolute value of the RTD conductance is greater than the antenna conductance.

The oscillation frequency of the circuit is determined by the inductor value, RTD capacitance and antenna capacitance. At resonance, the imaginary part of the antenna impedance is zero. This circuit exhibits an output power of -3.83 dBm at an oscillation frequency of 300 GHz with following simulated parameters: bias voltage $V_b = 0.65$ V, shorted capacitor $C_M = 200$ fF, transmission line impedance $Z = 50$ Ohm, electrical length $E = 16.6^0$, antenna resistance $R_A = 200$ Ohm. These are typical parameters for the RTD oscillator.

To investigate injection locking effect, antenna is replaced with an external source. Fig. 4 describes circuit model for simulation of the injection locking effect.

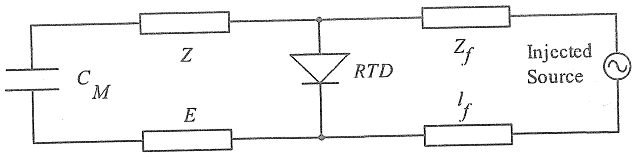


Fig. 4. Circuit model used for effect investigation

The RTD oscillator is coupled to an external source through free space whose parameters in this model are characteristic impedance $Z_f = R_A$ and physical length $l_f = 30$ mm. Here, the free space characteristic impedance is chosen to be equal to antenna resistance so that when the injected source does not exist this circuit model becomes the circuit shown in the fig.3. The detailed investigations of this circuit will be presented in the next section.

III. INJECTION LOCKING EFFECT OBSERVATION

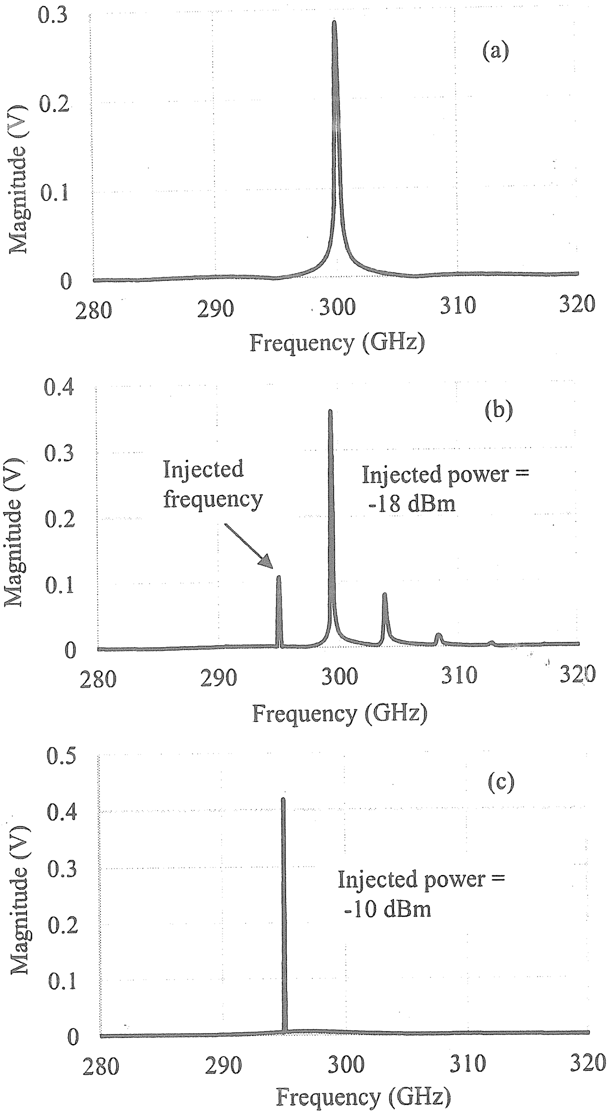


Fig. 5. Oscillation spectra, (a) free - running, (b) under pulling and (c) under locking

Fig. 5 illustrates the simulated results of the circuit shown in the Fig. 4. These results are derived from the transient analysis in the Keysight ADS simulator. Here the oscillation frequency of the free-running oscillator and the injected source are 300 GHz and 295 GHz, respectively. When the RTD oscillator is in the free running operation as shown in Fig. 5-a, the line width of oscillation spectra is relatively wide. On the other hand, in Fig. 5-b the oscillation spectra of the RTD THz oscillator under pulling by the injected source becomes narrower. Finally, Fig. 5-c indicates the most important situation when the RTD oscillator is fully locked to the injected source with a locked frequency of 295 GHz. This occurs if the power of the injected source is large enough compared to the RTD oscillation power. In fig. 5-b it can be seen that when the RTD oscillator is under pulling, output spectra comprises high level spurs along with the main frequency. In this case the injected source has a negative effect on the RTD oscillator. Whereas in figure 5-c, when the injection locking is fully satisfied, the output spectra is absolutely clean as the line width of oscillation spectra is very narrow and the spur levels are very small.

IV. RESULT DISCUSSIONS

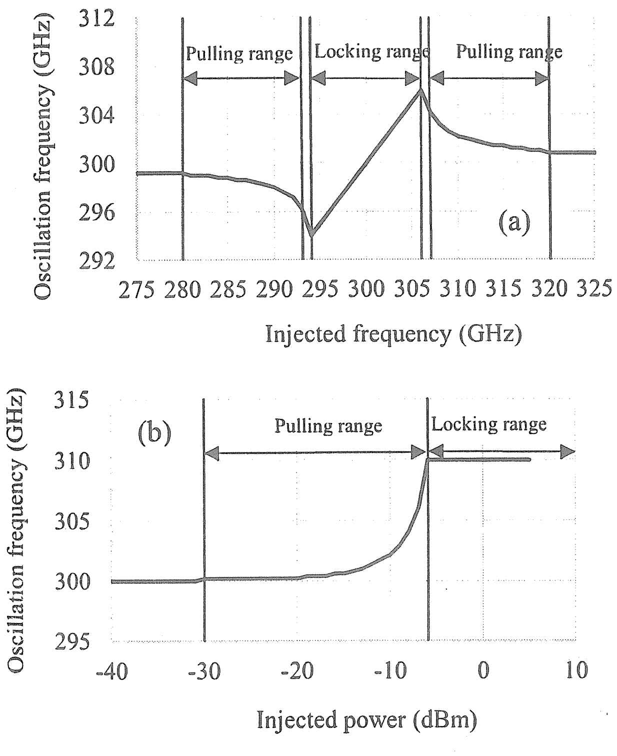


Fig. 6. Frequency (a) and power (b) characteristics

It is important to define locking and pulling ranges. Fig. 6-a describes the oscillation frequency of the RTD oscillator as a function of the injected frequency when the injected power is fixed at -10 dBm. The figure clearly shows the pulling range and locking range of the injection locking effect. In locking range oscillation frequency is exactly equal to injected frequency, whereas in pulling range the oscillation frequency varies between free-running and injected frequencies. In this case the pulling range is determined from 280 GHz to 293 GHz (13 GHz) and 306 GHz to 320 GHz (14 GHz). The locking range occurs from 294 GHz to 306 GHz (12 GHz). It can be clearly seen that when the injection locking occurs, the natural frequency of the RTD oscillator exactly equals the perturbing frequency of the injected source, demonstrating a good agreement with the general theory. Fig. 6-b shows power characteristic when the injected frequency is fixed at 310 GHz. In this figure, the pulling range is defined from -30 dBm to -6 dBm (24 dB) and locking range is defined from -6 dBm. It is obvious that the locking effect only occurs at the higher injected power.

To compare locking ranges at various frequencies of injected source, the frequency of the injected source is fixed at 310 GHz, 304 GHz and 296 GHz, respectively. Here the free-running oscillation frequency of the RTD oscillator is 300 GHz. The result is shown in the fig. 7.

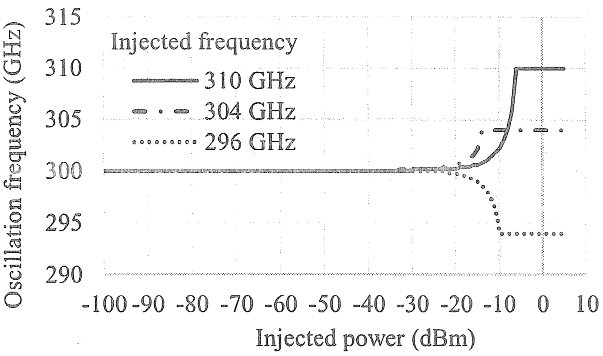


Fig. 7. Power characteristics at various injected frequencies

It is seen that the closer the injected frequency to the free-running frequency, the wider the locking range is. From this, it is possible for two or many RTD oscillators to be mutually coupled to each other in order to realize an oscillator array as the output power of the present RTD oscillator is on the order of -10 dBm.

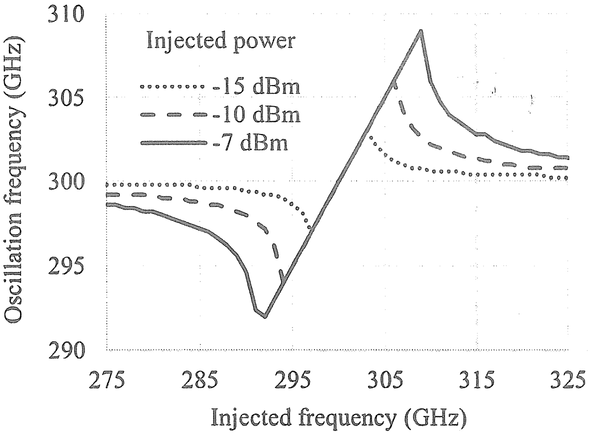


Fig. 8. Frequency characteristics at various injected powers

Fig. 8 shows frequency characteristics when the injected power is fixed at -15 dBm, -10 dBm and -7 dBm, respectively. It is clear that the higher the injected power, the wider the locking range is. It makes sense as the oscillator is easier to be locked to a strong injected source than to a weak one. In practice, wide locking range is always desirable. Although it is difficult to use high power injected sources in practical applications, a relatively high power source is sufficient for the locking to be occurred.

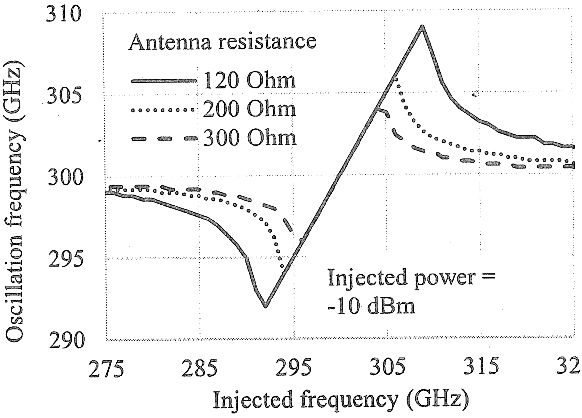
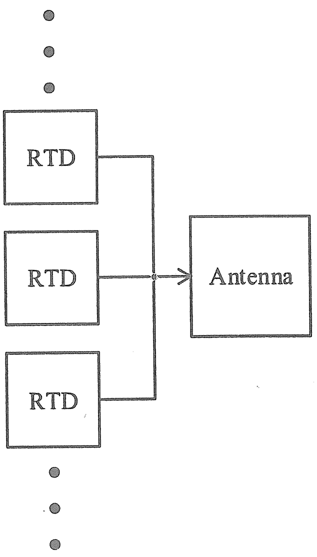


Fig. 9. Frequency characteristic at various antenna resistance

Fig. 9 shows the frequency characteristics of the injection locking effect at antenna resistance of 120 Ohm, 200 Ohm and 300 Ohm, respectively. It is obvious that locking range becomes narrower as the antenna resistance increases. This is because the antenna resistance affects the output power of the RTD oscillator. This conclusion plays a key role for the design of RTD injection locking oscillators, especially of the RTD oscillator array.

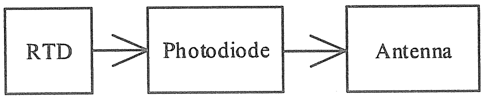
Proposed possible applications: From the above important discussions, promising THz applications based on the injection locking effect can be proposed as below:

- Coherent array oscillator.



In this proposed structure a number of RTD oscilators, which are placed closely to each others on the same substrate, are directly connected to the shared antenna, forming a coherent array oscillator.

- Improvement of stability by injection locking operation of RTD and photodiodes.



Here RTD oscillator and photodiode based optical source are mutually coupled, yielding improvement of stability of the RTD oscillator.

V. CONCLUSIONS

In this paper, injection locking effect in the THz RTD oscillators was investigated and simulated in the Keysight ADS simulator. The locking effect has been successfully observed, the locking range and pulling range were defined and discussed. It is found that the absolute locking range is wide, which is very important for many practical applications. Antenna resistance also has influence on locking range, which becomes narrower as antenna resistance increases. This result is especially meaningful for design of oscillators with specific desired locking range. Locking effect still occurs at relatively small injected power of -15 dBm, making it is possible to use RTD oscillators for array oscillators application. Various promising applications based on this effect have been proposed. The authors do believe the simulation approach used in this study implemented in Keysight ADS simulator can be a useful guideline for designs of THz injection locking based structures using RTDs.

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