Characterization of a hard-type oscillator using series-connected tunnel diodes

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Abstract: We characterize the bifurcational structure of the recently proposed hard-type oscillator using tunnel-effect devices. Such an oscillator succeeds in suppressing the spurious oscillation occurred in the bias line and exhibits large oscillation amplitude by device cascade, so that it has significant advantages for stable high-frequency signal generation. For experimental demonstration, we fabricate a test oscillator using tunnel diodes. Through bifurcational analyses, the test oscillator is shown to exhibit hard-type oscillation. We then carry out several time-domain measurements and succeed in confirming the advantages of the oscillator.

Keywords: tunnel diodes, hard-type oscillation, bifurcation

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

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1 Introduction

Resonant tunneling diodes (RTDs) have been attracting a great deal of attention for high-frequency signal sources including terahertz bands [1, 2, 3]. For such high frequencies, it becomes difficult to supply bias voltage to an RTD oscillator safely. The parasitic inductance and capacitance in the bias line of an oscillator may cause spurious oscillation supported by the broadband nature of negative differential resistance (NDR) of an RTD. This spurious oscillation variates the proper bias voltage level to make the original oscillation intermittent. The standard introduction of a stabilization resistor significantly increases the power consumption. When an oscillator has a stable limit cycle with a stable fixed point simultaneously, and can be designed to switch from the fixed point to the limit cycle only when a triggering voltage pulse is applied, it is called *hard-type* [4]. In contrast to the ordinary self-excited oscillators, also called soft-type oscillators, a hard-type oscillator is considered robust against the spurious oscillation in the bias line.

Fig. 1 shows the circuit diagram of the recently proposed hard-type RTD oscillator [5]. The resonance between L_r and C_r specifies the original oscillation, while that between L_b and C_b simulates the spurious oscillation relating with the bias voltage V_b , which is supposed to be suppressed by the resistor R_b in series with L_b . The RTD exhibits NDR only in restricted voltage range, such that self-excited oscillation scarcely occur. To trigger the oscillation, an FET is connected to the oscillation node. A trigger pulse V_{trg} applied to the FET gate pulls down the voltage to excite the original oscillation. In general, the relatively narrow voltage range exhibiting NDR limits the oscillation amplitude of RTD-based oscillators [6]. The proposed oscillator also contributes to overcoming this difficulty by the introduction of series-connected RTDs [5] $D_1, \dots, D_n$ ($n > 1$) in Fig. 1. In general, the DC operating points in NDR regions of the circuit using series-connected RTDs are unstable [7], i.e., the RTDs cannot be biased in the NDR region at the same time. 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

Fig. 1. Circuit diagram of proposed oscillator.

region present in greater voltages than the NDR one. The application of the triggering pulse can eliminate this unbalanced DC points. By setting the rise- and fall-times of the triggering pulse to be so small that the increasing rate of the biasing voltage becomes higher than the growth rate of the difference in biasing voltage, we succeed in biasing all the RTDs in NDR region. The resulting wide voltage range exhibiting NDR, the circuit begins to oscillate. 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, which becomes n times as large as that of a single-RTD oscillator.

2 Bifurcational structure

In this study, we characterize the bifurcational structure of the proposed oscillator and carry out experimental demonstration of its operation principles using tunnel diodes (TDs) instead of RTDs. To clarify the bifurcational structure of the proposed oscillator, we carry out several calculations using AUTO [8, 9]. The governing equations of the circuit are given by

$$\dot{I}_b = -L_b^{-1}(V_a - V_b + R_b I_b), \quad (1)$$

$$\dot{V}_a = -C_b^{-1}\{I_{TD}(V_a - V_c) - I_b\}, \quad (2)$$

$$\dot{I}_r = L_r^{-1}(V_c - R_r I_r), \quad (3)$$

$$\dot{V}_c = C_r^{-1}\{I_{TD}(V_a - V_c) - I_r\}, \quad (4)$$

where V_b , V_a , V_c , I_b , and I_r represent the bias voltage, the anode voltage of the TD, cathode voltage of the TD, current flowing through L_b , and current flowing through L_r , respectively, and $\dot{X}$ represents the temporal derivative of any X . Here, L_r , C_r , and R_r are set to $1.0\ \mu\text{H}$, $500\ \text{pF}$, and $0.0\ \Omega$, respectively, while R_b and V_b are employed as the bifurcation parameters. Notice that the FET section is removed, because it only triggers oscillation and does not influence the bifurcational structure. As a result, the system is four dimensional. As mentioned above, L_b and C_b simulate the bias-line parasitics. We first examine how the bifurcational structure varies by L_b and C_b . Explicitly, we set $L_b = \alpha L_r$ and $C_b = \alpha C_r$ and carry

Fig. 2. Two-parameter continuation of fixed point.

out AUTO calculations for $\alpha = 1, 10, 100$, and 1000 , resulting in the fact that the bifurcational structure does not alter significantly when α exceeds 10 . We thus mention the results obtained for $\alpha = 1$ and 10 . For AUTO calculations, we first set V_b to 0.0 , where a unique stable fixed point is $(I_b, V_a, I_r, V_c) = (0, 0, 0, 0)$. Notice that the bifurcation of a fixed point is determined only by the circuit's DC characteristics, while the periodic solutions are largely dependent on reactances. Fig. 2 shows the resulting fixed-point bifurcation. For R_b values greater than the cusp bifurcation point CP , a fold bifurcation curve t divides the parameter space into two. The saddle appeared in the region surrounded by t corresponds to the NDR cross point between the TD current-voltage curve and load line. Besides, four Andronov-Hopf bifurcation points are found, where the continuation of corresponding periodic solutions follows. All the periodic solutions emanating from two of them are examined to be unstable; therefore, we only characterize remaining two ($h_{1,2}$ in Fig. 2) in what follows. For small R_b values, $h_{1,2}$ are supercritical and become subcritical at the Bautin bifurcation points $GH_{1,2}$. Fig. 3 shows the results of continuation of the periodic solutions with respect to V_b for several fixed values of R_b . L^2 -norm is vertically shown. R_b is set to $50, 80, 100$, and 200Ω in Figs. 3(a), (b), (c), and (d), respectively. Labels $\times 1$ and $\times 10$ correspond to $\alpha = 1$ and 10 , respectively. Moreover, red and blue curves represent the stable fixed-point and periodic-solution trajectories, respectively, while any unstable trajectories are shown by black curves. In each figure, we can see that finite range of V_b allows the coexistence of a stable fixed point and a stable limit cycle. In Fig. 3(a), the stable fixed-point trajectory does not have any overlap because R_b is set to a value less than that corresponding to CP . In addition, any Andronov-Hopf bifurcation are supercritical for h_1 . Although the V_b range where stable periodic solution exists has a tendency to become narrower for smaller α , that dependence on α is not so significant that the circuit potentially succeeds in hard-type oscillation for practical

Fig. 3. Continuation of periodic solution. R_b is set to (a) 50 , (b) 80 , (c) 100 , and (d) 200Ω .

Fig. 4. Bifurcation structure for hard-type oscillation.

bias-line parasitics. The coexistence of a stable fixed point and a stable limit cycle is insufficient for hard-type oscillation. It requires that the transient of bias voltage secures the route from the fixed point to the limit cycle. Fig. 4 shows several bifurcation patterns that potentially lead to hard-type oscillation with sufficiently slow V_b transients, assuming the system initially occupies the point on the first stable fixed-point branch, defined by the trajectory obtained by the fixed-point continuation from $(I_b, V_a, I_r, V_c) = (0, 0, 0, 0)$. In Figs. 4(a) and (b), a unique stable fixed point and a unique stable periodic solution exist at the bias point (circles in Fig. 4(a)). The difference between Figs. 4(a) and (b) is the presence of the overlap in the stable fixed-point branch. In either case, the circuit succeeds in hard-type oscillation only when the system state reaches the periodic-solution branch exceeding the right end of the first stable fixed-point branch (V_{bu} in Fig. 4) by the application of a trigger pulse. In Fig. 4(a), the system eventually reaches the periodic-solution branch, even when it fails to switch to the periodic-solution branch directly but gets to the second fixed-point branch passing V_{bu} . This robustness is lost in Fig. 4(b), where there occurs finite possibility the system finally returns to the original fixed point on the first branch. In contrast, Fig. 4(c) exhibits two stable fixed points and a unique stable periodic solution at the bias point. Once the trigger pulse moves the system state beyond the green dotted line, the circuit fails in hard-type oscillation because the state has to be on the second fixed-point branch eventually. By these observations, the oscillator has to be designed to achieve bifurcation shown in Fig. 4(a) for definite hard-type oscillation; therefore, R_b should be set to around $50\ \Omega$ for parameter values to obtain Fig. 3 because Fig. 3(a) realizes the robust bifurcation structure. Figs. 3(b) and (c) correspond to the case shown in Fig. 4(b). Hence, the oscillator possibly achieves hard-type oscillation for $R_b \approx 100\ \Omega$. Finally, hard-type oscillation cannot be established for $R_b = 200\ \Omega$ because no stable periodic solution exists at $V_b = V_{bu}$. Notice that the fixed point on the second stable fixed-point branch can be skipped, when the V_b varies with the higher frequency than the absolute value of the Lyapunov exponent of that fixed point; therefore, the oscillator can leave room to achieve hard-type oscillation in the cases other than that shown in Fig. 4(a).

3 Experimental demonstration

In this short letter, we demonstrate the most important properties of the proposed oscillator: hard-type oscillation and increase in amplitude by device cascade. A test oscillator is fabricated on a breadboard using NEC 1S1763 Esaki diodes as TDs and TOSHIBA 2SK30A JFET in the trigger section. Moreover, L_r and C_r are set to

Fig. 5. Measured time-domain waveforms for (a) single- and (b) double-TD oscillators.

1 μH and 47 pF. To simulate the situation setting α to 10 we employ 10- μH inductor and 470-pF capacitor as L_b and C_b , respectively. In addition, R_b is set to 100 Ω . To examine whether the oscillator achieves hard-type oscillation or not, both the trigger and bias voltages are applied in the form of short and wide pulses, respectively, and are phase-synchronized. The voltage at the cathode of TD is detected by Agilent 1134A active probe. Fig. 5(a) shows the voltage measured for the oscillator with the single TD. The spurious oscillation is shown to be suppressed. In addition, it is established that the oscillation begins only after the time the trigger pulse is applied, i.e., the oscillator is actually hard-type. The measured oscillation frequency is 13.47 and 16.37 MHz for Figs. 5(a) and (b), respectively. The oscillating waveform is influenced by the relaxation oscillation mode [10]. On the other hand, Fig. 5(b) shows the detected voltage for the oscillator with two TDs. The oscillation amplitude becomes twice as large as that observed in the single-TD oscillator.

4 Conclusions

Bifurcational analyses of recently proposed hard-type oscillator ensure the coexistence of a stable fixed point and a stable limit cycle, and the route from the former to the latter. Time-domain measurements succeed in hard-type oscillation and the amplitude increase by series-connected TDs.