Behavior of Gunn Diode Oscillator with a Moving Reflector as a Self-Excited Mixer and a Load Variation Detector

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Abstract—Behavior of a Gunn diode oscillator with a moving reflector is described. Two cases are considered: The oscillator acts as 1) self-excited mixer and 2) load variation detector. Analyses are carried out by using a simplified model of the dynamic current–voltage characteristic of the Gunn diode oscillator. Experiments have been also carried out. For case 1), an external signal was injected into the oscillator instead of the signal reflected by the reflector. For case 2), the effects of the moving reflector upon the oscillation frequency and dc current were investigated in the static condition. In 1), conversion gain greater than 20 dB has been obtained analytically and experimentally. In 2), it is shown that dc current and the oscillation frequency changes sinusoidally with the phase of reflection coefficient. We can obtain information about the moving reflector through the bias port of the oscillator in both cases.

I. Introduction

Microwave solid-state oscillators such as Gunn and IMPATT oscillators are coming into practical use. They are attractive devices because of their compactness, low power consumptions, and ease of treatment.

Several devices have been developed using Gunn and IMPATT oscillators as a transmitter oscillator as well as a receiver detector [1], [2]. In these devices, a part of the radiated power is reflected by a moving reflector and injected into the oscillator: the oscillator is terminated by a moving load.

Many authors discussed Gunn and IMPATT oscillators when 1) the external signal was injected [3], [4] and when 2) the load of oscillator was varied [5].

In this paper, these two cases are considered to be extreme cases for a Gunn oscillator with a moving reflector. Case 1) is one extreme case when the speed of the reflector is so large that the oscillator is not phase-locked by the Doppler shifted signal. The oscillator acts as a self-excited mixer. Case 2) is another extreme case when the speed is quite small. In this case, we call the oscillator "load variation detector." Information about the reflector is obtained through the bias port in both cases. Performances of the oscillator for both cases are analyzed using a simplified dynamic current–voltage characteristic of a Gunn diode oscillator. Experimental results are also described. For case 1), an external signal is injected into the oscillator instead of the reflected signal. For case 2), the effects of the reflector upon the oscillator performances are investigated.

Qualitatively, the conditions necessary for each case are also described.

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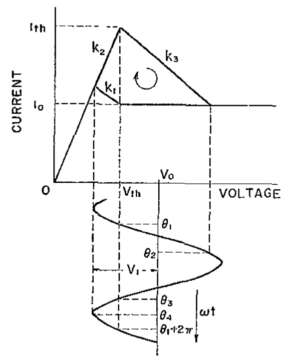

Fig. 1. Model of dynamic current–voltage characteristic of Gunn diode ($k_1 = -[k_2(V_0 - V_1) - i_0]/(V_1 + V_{th} - V_0)$, $k_2 = i_{th}/V_{th}$).

II. Simplified Dynamic I–V Model and Calculated Characteristics of a Gunn Diode Oscillator

The dynamic current–voltage characteristics of the Gunn diode are complicated. They depend upon the impurity density and its profile as well as operating modes [6]. For simplicity of the following analyses, we set up a simple model for the dynamic current–voltage characteristic which is independent of the operating frequency. Let us assume that only the fundamental ac voltage appears at the device terminal except for bias voltage and that the dynamic current–voltage characteristic of the Gunn diode is a loop made of straight lines in the I–V plane, as shown in Fig. 1. V_0 is bias voltage and V_{th} and i_{th} are threshold voltage and the corresponding current, respectively, k_1, k_2, and k_3 show the gradient of each straight line in the I–V plane where $k_2 = i_{th}/V_{th}$. Gradient k_1 is assumed to be determined by the minimum value of the terminal voltage. Physical meanings of the I–V characteristic are as follows. High-field domain builds up in the period between θ_1 and θ_2, travels toward the anode between θ_2 and θ_3, and disappears into the anode between θ_3 and θ_4 where terminal voltage $\tilde{V}$ is given by $\tilde{V} = V_0 + V_1 \sin(\omega t)$. The domain does not exist in the active layer of the diode between θ_4 and $\theta_1 + 2\pi$. This situation corresponds to the delayed domain mode [6].

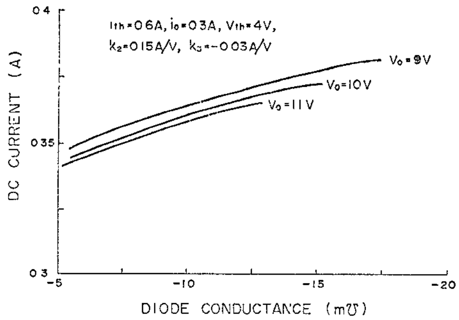

Fig. 2. Dc current through Gunn diode as a function of bias voltage V_0 and large-signal diode conductance ($V_{th}=4$ V, $i_{th}=2i_0=0.6$ A, $k_3=-0.03$ A/V).

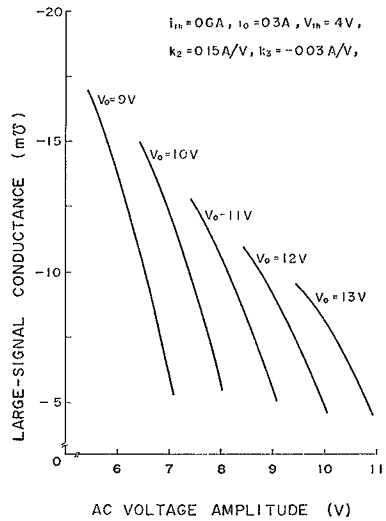

Fig. 3. Large-signal conductance as a function of bias voltage V_0 and ac voltage amplitude V_1 ($V_{th}=4$ V, $i_{th}=2i_0=0.6$ A, $k_3=-0.03$ A/V).

Dc current I_0 and large-signal admittance of the diode Y_d are given by

$$I_0 = \frac{\omega}{2\pi}\int_0^{2\pi/\omega} i(t)dt \tag{1}$$

$$Y_d = \frac{\mathrm{Re}\,(I_1) + j\,\mathrm{Im}\,(I_1)}{V_1} \tag{2}$$

respectively, where

$$\mathrm{Re}\,(I_1) = \frac{1}{\pi}\int_0^{2\pi} i(t)\sin\omega t d(\omega t)$$

$$\mathrm{Im}\,(I_1) = \frac{1}{\pi}\int_0^{2\pi} i(t)\cos\omega t d(\omega t).$$

I_0 and Re (Y_d) have been numerically calculated under the conditions that $V_{th}=4$ V, $i_{th}=2i=0.6$ A, $k_2=0.15$, and $k_3=-0.03$ A/V and are shown in Figs. 2 and 3. The absolute value of the conductance decreases with the increase of ac voltage. This implies that one can obtain stable oscillation in a simple cavity constructed by the parallel combination of R, L, and C components [7]. It is shown in Fig. 2 that dc current increases linearly with the increase of the load conductance (which is equal to the inverse sign of the diode conductance).

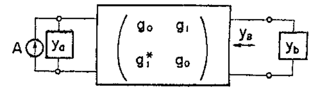

Fig. 4. Simplified equivalent circuit of self-excited mixer.

Let us define sensitivity S as the ratio of relative excursion of dc current versus that of load conductance, i.e.,

$$S \equiv \frac{\Delta I/I_0}{\Delta G/G_{LO}} \tag{3}$$

where I_0 is the value of dc current I when the load conductance G_L is equal to a specific value G_{LO} and $\Delta I = I - I_0$ and $\Delta G = G_L - G_{LO}$. S is a positive value as seen from (3) and Fig. 2.

III. Analyses

A. Self-Excited Mixer

Any oscillator acts as a self-excited mixer because of the nonlinearity of the current–voltage characteristic unless it is phase locked. Conversion gain greater than unity may be obtained because of the negative differential conductance.

Let us analyze the mixer action of a Gunn oscillator by small-signal theory [8], utilizing the model of dynamic current–voltage characteristic. Fig. 4 shows the simplified equivalent circuit of the self-excited mixer where $y_a = -Y_d$ for a fixed V_1. It is assumed that the equivalent internal admittance of the signal generator is equal to y_a. It is also assumed that the circuit impedance for all other signals but the incoming and the IF signals are zero and the IF terminal is terminated by load admittance y_b, where the imaginary part of y_b is taken to be equal to the negative value of the IF output susceptance Im (y_β).

IF output admittance y_β is given by

$$y_\beta = g_0 - \frac{|g_1|^2}{g_0 + y_a} \tag{4}$$

where g_0 and g_1 are the zero- and the first-order terms of differential conductance, respectively. The value of Re (y_β) is numerically calculated and is shown in Fig. 5. It is negative in the range of bias voltage and ac voltage amplitude in which we are interested.

Conversion gain G is defined as the ratio of the IF-signal power output P_{IF} versus the available power of microwave-signal generator P_1, i.e.,

$$G = P_{IF}/P_1 \tag{5}$$

where

$$P_1 = \frac{|A|^2}{4\,\mathrm{Re}\,(y_a)} \tag{6}$$

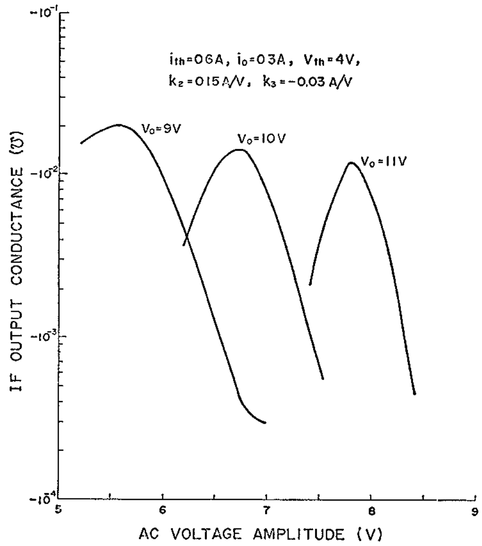

Fig. 5. IF output conductance Re (y_β) as a function of bias voltage V_0 and ac voltage amplitude ($V_{th}=4$ V, $i_{th}=2i_0=0.6$ A, $k_3=-0.03$ A/V).

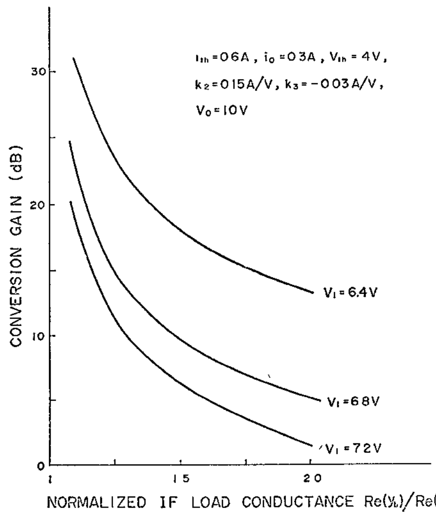

Fig. 6. Conversion gain for a fixed bias voltage (10 V) as a function of ac voltage V_1 and normalized IF load conductance Re (Y_b)/Re (Y_β) ($V_{th}=4$ V, $i_{th}=2i_0=0.6$ A, $k_3=-0.03$ A/V).

$$P_{IF} = \frac{\mathrm{Re}\,(y_b)}{[\mathrm{Re}\,(y_\beta)+\mathrm{Re}\,(y_b)]^2}\cdot\frac{|g_1|^2|A|^2}{|g_0+y_a|^2} \tag{7}$$

and A is current amplitude of the constant current generator. Calculated conversion gains are shown in Fig. 6. We can obtain the conversion gain greater than 20 dB by using a reasonable circuit condition.

B. Load Variation Detector

Dc current through the Gunn diode is a function of the microwave load conductance as described in Section II. Therefore, information about the variation of load conductance can be obtained by the variation of dc current.

The action of the oscillator, with a single output port across which the load admittance is Y_L at the detuned short position, is given by [7]

$$-\frac{Y_d}{C\omega_a} = j\left(\frac{\omega}{\omega_a}-\frac{\omega_a}{\omega}\right)+\frac{1}{Q_a}+\frac{y_L}{Q_e}, \qquad y_L=\frac{Y_L}{Y_0} \tag{8}$$

where ω_a, Q_a, and Q_e are the resonant angular frequency, unloaded Q, and external Q of the resonant cavity, respectively, Y_0 is the characteristic admittance of the line connected to the cavity, Y_d is the electronic admittance of the Gunn diode, and C is the equivalent capacitance of the cavity containing the stray capacitance of the Gunn diode.

Let us consider the case in which a slowly moving reflector with the reflection coefficient ρ is connected to the output port. We assume that the load admittance y_L is given by

$$y_L = \frac{1-\rho e^{-j(2\omega/c)(l+v(t-t_0))}}{1+\rho e^{-j(2\omega/c)(l+v(t-t_0))}} \tag{9}$$

where c is the light velocity, v is the velocity of a load which is positive when a reflector is receding, and l is the distance between the reflector and the detuned short position at $t=t_0$: the frequency of the incoming signal is equal to that of the output signal even if the reflector is receding or approaching the oscillator. From (8) and (9), the differences in load conductance G_L and oscillation frequency f for $\rho=0$ and $\rho\neq 0$ are given by

$$\Delta G/G_{LO} = -2|\rho|\cos\theta \tag{10}$$

$$\Delta f/f_0 = \frac{|\rho|\sin\theta}{Q_e} \tag{11}$$

$$\theta = \arg(\rho) - \frac{2\omega}{c}(l+v(t-t_0)) \tag{12}$$

where $\Delta G = G_L - G_{LO}(G_{LO}=G_L|_{\rho=0})$ and $\Delta f = f - f_0$ $(f_0 = f|_{\rho=0})$. It is assumed that $Q_a \gg Q_e$, Im $(Y_d)=0$, and $|\rho| \ll 1$. The load conductance and the frequency vary sinusoidally. The phases differ from each other by $\pi/2$ rad. From (3) and (10), $\Delta I/I_0$ is given by

$$\Delta I/I = -2S|\rho|\cos\theta. \tag{13}$$

Dc current varies sinusoidally. The period is $2vf/c$. Thus we are able to know the speed of the slowly moving reflector. Since S is positive, it is seen from (11) and (13) that the phase of variation of dc current leads (or lags) that of frequency by $\pi/2$ rad when the reflector recedes (or approaches) the oscillator.

IV. Experimental Results

A. Self-Excited Mixer

It is difficult to investigate the self-excited-mixer action of a Gunn oscillator by moving a reflector. In order to obtain reliable results, we have investigated the mixer action experimentally by use of another oscillator instead of a moving reflector.

A schematic diagram of the test circuit is given in Fig. 7. The input signal (frequency: f_1, power: P_1) is injected into the Gunn oscillator (free-running frequency: f_0, output power: P_0) through a circulator. The free-

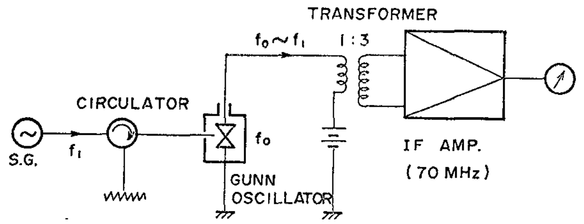

Fig. 7. Schematic diagram of the test circuit for self-excited mixer.

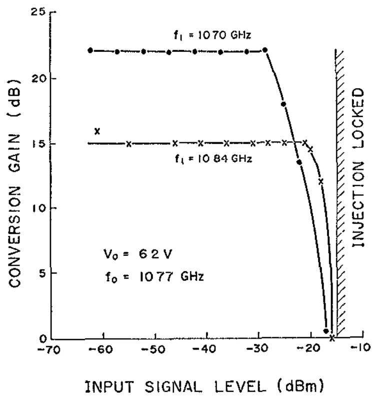

Fig. 8. Measured conversion gain as a function of input-signal level ($V_0=6.2$ V, $f_0=10.77$ GHz, $f=70$ MHz).

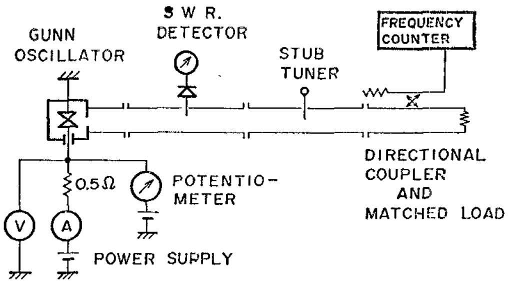

Fig. 9. Schematic diagram of the test circuit for load variation detector.

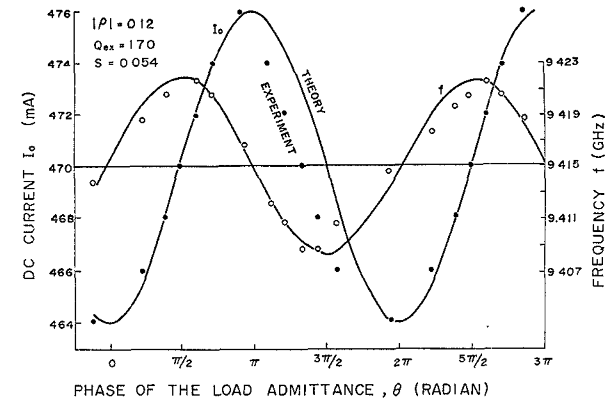

Fig. 10. Dc current as a function of the phase of reflection coefficient ($|\rho|=0.12$, $Q=170$).

running frequency f_0 is 10.78 GHz and the input-signal frequency f_1 is higher or lower than f_0 by 70 MHz. The IF signal (frequency: 70 MHz) is taken out by means of a transformer (turn ratio is 1:3) and subsequently amplified by a preamplifier whose input impedance is 140 Ω. The low-field resistance R_0, threshold voltage V_{th}, and the corresponding current I_{th} are 6.6 Ω, 3.8 V, and 380 mA, respectively.

The conversion gain for a fixed bias voltage is plotted in Fig. 8 as a function of input power P_1. The conversion gain greater than 20 dB has been obtained. Injection locking occurs for $P_1 > -15$ dBm. Small-signal gain ($P_1 = -40$ dBm) has been investigated as a function of bias voltage. In this case, f_1 was adjusted to make the IF signal frequency equal to 70 MHz since the free-running frequency varies with the variation of the bias voltage. The conversion gain decreases with the increase of bias voltage [1].

Noise figure of the self-excited mixer has also been measured. A typical value of NF is as large as 40 dB.

B. Load Variation Detector

A schematic diagram of the test circuit is given in Fig. 9. The phase of the reflection coefficient was varied by more than 2π rad by sliding the stub-tuner. Dc current was measured by the potentiometer. The peak-to-peak value of the dc-current variation was negligibly small compared with the dc current at $\rho=0$. The results are shown in Fig. 10. Both the dc current and the frequency change in the nearly sinusoidal form with θ. The phase difference between them is about $\pi/2$ rad as expected from [11] and [13].

Qualitatively, the same results have been obtained for a slowly moving reflector. In this case, the frequency and the dc current were observed on a dual-beam oscilloscope where the FM signal was converted into AM signal by means of a microwave discriminator. The direction of the motion was distinguished by observing the phase relation between dc current and oscillation frequency.

From (13), the peak-to-peak value of the dc current is given by

$$\Delta I_{p-p} = 4 I_0 S |\rho|. \tag{14}$$

Although (14) is valid only for the case where Im $(Y_d)=0$ and $|\rho| \ll 1$, we assumed that (14) is applicable for the oscillator under test. The experimental values of ΔI_{p-p} are plotted in Fig. 11, as a function of $|\rho|$. ΔI_{p-p} increases linearly with the increase of $|\rho|$, as expected from (14).

The sensitivity S has been estimated by utilizing the measured values of ΔI_{p-p}, I_0, $|\rho|$, and (14). The results are shown in Fig. 12 as a function of bias voltage. The square shows the point at which the maximum power output is obtained.

VI. Discussion

In general, the oscillator with a moving reflector will behave in a very complicated manner. The behavior of the oscillator should be determined by the velocity of the reflector, the magnitude of the reflected power, and the circuit conditions of the oscillator.

We have considered the behavior in the two extreme

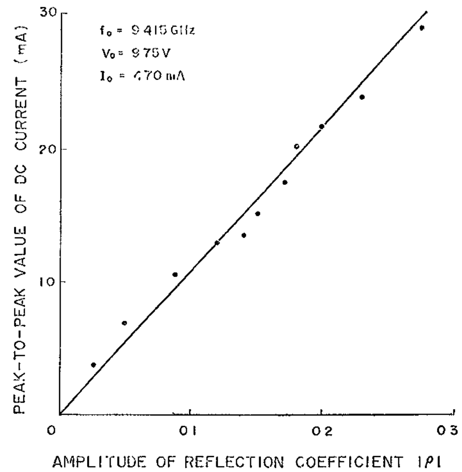

Fig. 11. Peak-to-peak value of dc current as a function of amplitude of reflection coefficient ($f_0=9.415$ GHz, $V_0=9.75$ V, $I_0=470$ mA).

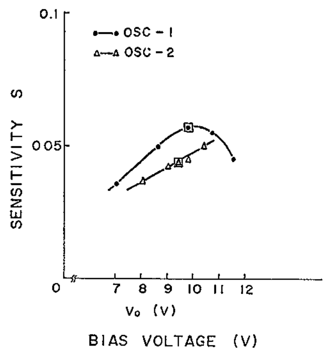

Fig. 12. Measured sensitivity S as a function of bias voltage (squares show the power maximum point).

cases. Let us give a qualitative discussion on the conditions necessary for each case. If the velocity of the reflector is so large that the relationship between powers and frequencies is given by

$$\frac{P_1}{P_0} \ll \left(Q_e \frac{f_d}{f_0}\right)^2$$

where P_1 and P_0 are the reflected and the generated power, respectively, f_0 is the free-running frequency and f_d is the Doppler frequency, the large-signal performance of the oscillator is hardly affected by the reflected signal. The oscillator acts as a self-excited mixer.

If the velocity of the reflector is so small that the period of the Doppler signal is much larger than the response time of the oscillator, the large-signal performance is changed by the reflected power. The oscillator acts as a load variation detector provided that both the ac voltage amplitude and the phase of the signal generated in the oscillator respond immediately to the variation of circuit condition. Immediate response of voltage amplitude can be obtained if the relaxation time of the cavity including the Gunn diode is much smaller than the period of the Doppler signal. In other words, it is given by

$$Q_L \ll \pi c/2v$$

where Q_L is the loaded Q of the oscillator. This condition is valid for the ordinary oscillator and velocity of a moving reflector. Another condition is that the phase response be much faster than the period. This response time is determined by Q_e, frequency and phase difference between the incoming signal and output signal, and power level [9], [10]. In general, the response time decreases with the decrease of Q_e.

VII. Conclusion

The behavior of the Gunn oscillator with a moving reflector has been described in the two extreme cases when the velocity of the reflector is very large or very small. In these cases, the oscillator acts as 1) self-excited mixer and 2) load variation detector. We can obtain the information about the moving reflector through the bias port of the oscillator in both cases. In 1), the conversion gain greater than unity has been obtained analytically by using a simple model of the Gunn diode. The conversion gain greater than 20 dB has been obtained experimentally by utilizing an external oscillator instead of the rapidly moving reflector. In 2), dc current through the Gunn diode and the oscillation frequency vary periodically, and their phases differ from each other by $\pi/2$ rad. This has been ascertained experimentally for the static condition and also for a slowly moving reflector.

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