A Highly Stabilized MIC Gunn Oscillator Using a Dielectric Resonator

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***Abstract*—An *X*-band frequency-stabilized MIC Gunn oscillator of a very simple structure using a dielectric resonator is developed. It is studied how the oscillating characteristics can be controlled by circuit parameters, with special attention to the factors affecting the frequency stability with temperature. By optimizing these factors and by selecting the proper temperature coefficient of a newly developed dielectric resonator, the high frequency stability of less than ±100 kHz over the temperature range from −20 to 60°C (2×10^{-7}/°C) was obtained.**

I. Introduction

As a method of constructing a microwave integrated circuit (MIC) Gunn oscillator, it is well known to mount a Gunn diode in a microstrip resonator [1], [2]. An MIC Gunn oscillator with a microstrip resonator, however, has poor temperature stability because of the large temperature dependence of Gunn diode parameters and the low quality factor of the microstrip resonator; such an oscillator is improper for a local oscillator application. What is worse is that in order to obtain the desired output power and oscillation frequency with such an oscillator, it is necessary to determine the microstrip pattern suitable to the diode characteristics by trial and error method. The variation of oscillator characteristics due to that of the diode characteristics may be large mainly because of the low quality factor of the microstrip resonator. To use an MIC Gunn oscillator as a local oscillator, for example, in a SHF television receiver [3], low cost and high frequency stability are essential.

In recent years, dielectric resonators of low loss and high temperature stability have been developed [4], and MIC oscillators with a dielectric resonator have been shown to have high frequency stability and low noise performance [5], [6]. However, it has not been reported how the oscillator characteristics can be controlled by various circuit parameters.

The purpose of this paper is to study the characteristics of an MIC Gunn oscillator of a simple structure using a dielectric resonator. It is studied how the oscillating characteristics can be controlled by several parameters, such as the position and resonant frequency of the dielectric resonator and the bias voltage. The factors affecting the frequency stability with temperature are also studied. Based on these investigations, the frequency stabilization is examined by using a newly developed dielectric resonator, whose temperature coefficient can easily be changed. As a result, the high frequency stability, of less than ±100 kHz over the temperature range from −20 to 60°C, has been realized by selecting the temperature coefficient of the resonant frequency of the dielectric resonator to be 5 ppm/°C.

Manuscript received November 6, 1978; revised March 13, 1979.
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II. Oscillator Configuration

The construction of the oscillator is shown in Fig. 1(a) and (b), which shows the circuit layout and a cross-sectional view of the oscillator. By using a thick film technology for the purpose of lowering the cost, the circuit was formed on a 0.635-mm thick alumina substrate of relative dielectric constant 9.4. A packaged Gunn diode was mounted to a grounded heat sink, so that the ceramic ring of it was in contact with the edge of the alumina substrate. The top electrode of the diode was connected electrically to a 50-Ω microstrip conductor by soldering. The $TE_{01\delta}$-mode cylindrical dielectric resonator was placed in the vicinity of a 50-Ω microstripline, the resonator center position l, being about $\lambda g/4$ away from the end of the microstripline. The dielectric resonator, therefore, operates both as a resonator and an impedance transformer. The resonant frequency is changed by adjusting the air gap x, in Fig. 1(b).

III. Operational Principles and Controlling Parameters

A. Equivalent Circuit and Operational Principles

Few works have been reported on the equivalent circuit of a packaged diode mounted in a microstripline [7], [8]. The equivalent circuit seen from a diode chip may be expressed by Fig. 2. The diode-chip admittance Y_D is transformed by a lossless-immitance transformation circuit and connected to a 50-Ω microstripline. The parameters of the transformation changes considerably with the diode package and mounting structure. For convenience of the later description, we express the impedance of a diode seen from the end of a 50-Ω line by $Z_d = -R_d + jX_d$, including the lossless-immittance transformation circuit.

The equivalent circuit of the dielectric resonator magnetically coupled to a microstripline as a band-rejection filter is represented by a parallel resonant circuit as shown

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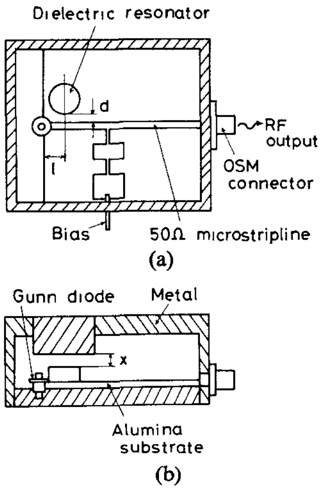

Fig. 1. Construction of the present oscillator. (a) The circuit layout. (b) The cross-sectional view.

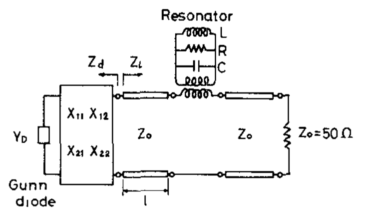

Fig. 2. Equivalent circuit of the oscillator.

in Fig. 2 [6]. If we denote the distance between the reference plane and the resonator-center position by l, the normalized load impedance seen from the reference plane at the end of a 50-Ω line is expressed as

$$z_l \equiv \frac{z_l}{Z_0} \equiv \frac{R_l + jX_l}{Z_0} = r_l + jx_l$$

$$= \frac{(\rho - Q_0 v_0 \tan\theta) + j(Q_0 V_0 + \tan\theta)}{(1 - Q_0 v_0 \tan\theta) + j(Q_0 V_0 + \rho\tan\theta)} \tag{1}$$

where

$$\rho = 1 + \frac{k^2 R}{Z_0} \qquad v_0 = \frac{f}{f_0} - \frac{f_0}{f} \qquad \theta = \frac{2\pi}{\lambda g} l. \tag{2}$$

The ρ is the VSWR of the resonator terminated by a matched load at its resonant frequency. The f_0 and Q_0 represent the resonant frequency and unloaded Q of the resonator, respectively. The k is the coupling coefficient between the resonator and the microstripline. If l is chosen as $l = \lambda g/4$, (1) can be approximated by

$$r_l = 1 - \frac{(\rho - 1)\rho}{\rho^2 + (2Q_0\delta)^2} \tag{3}$$

$$x_l = \frac{(\rho - 1)2Q_0\delta}{\rho^2 + (2Q_0\delta)^2} \tag{4}$$

where

$$\delta = \frac{f - f_0}{f_0}. \tag{5}$$

Equations (3) and (4) have the same forms as the equations derived by Kohiyama and Momma [9], except that the admittance of their results has been replaced by an impedance of our oscillator. The operational principles of our oscillator are, therefore, essentially the same as those of their oscillator. In the case of our oscillator, the load seen from a diode assumes a single-series resonant impedance in the vicinity of the resonant frequency of the resonator. The load impedance as a function of f is shown in Fig. 3, where the derivative of x_l with respect to f, $\partial x_l/\partial f$ is negative in regions I and III, and positive in region II. Therefore, oscillation is possible only in region II. The width δ_s of region II is given by, from (4),

$$\delta_s = \frac{\rho}{Q_0} \tag{6}$$

which is identical to Kohiyama and Momma's result [9].

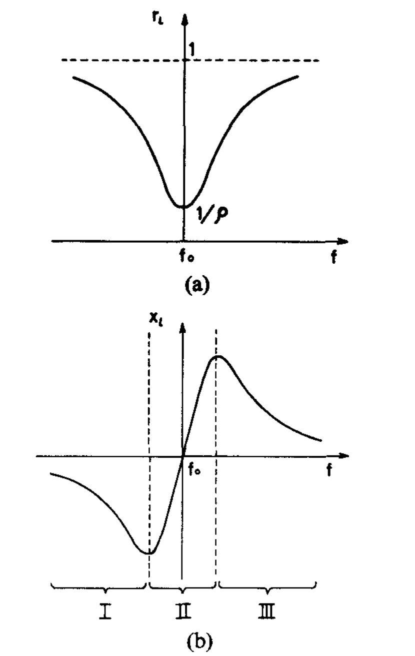

Fig. 3. Normalized load impedance. (a) The load resistance. (b) The load reactance.

B. Parameters Controlling the Oscillating Characteristics

In the case of our oscillator, the following parameters were taken as controlling parameters (Fig. 1):

1) distance d between the resonator edge and the microstripline edge,
2) distance l between the center position of the dielectric resonator and the reference plane of a diode located at the end of the microstripline,
3) air gap x between the resonator and the metal disk.

Fig. 4 shows the normalized load impedance $z_l = r_l + jx_l$ calculated by (1) when $Q_0 = 3500$ and $l = \lambda g_0/4$(λg_0 denotes the wavelength at f_0). We see that the diameter of the impedance locus becomes larger as ρ increases, and that the change rate of the load reactance increases as ρ decreases. The ρ is a function of k as is seen from (2), and hence is a function of d. The relation between ρ and d can be obtained experimentally. This will be described in Section IV. Fig. 5 shows the loci of z_l, when $l = 0.8 l_0$, $l = l_0 \equiv \lambda g_0/4$, and $l = 1.2 l_0$ ($Q_0 = 3500$, $\rho = 20$). Since the

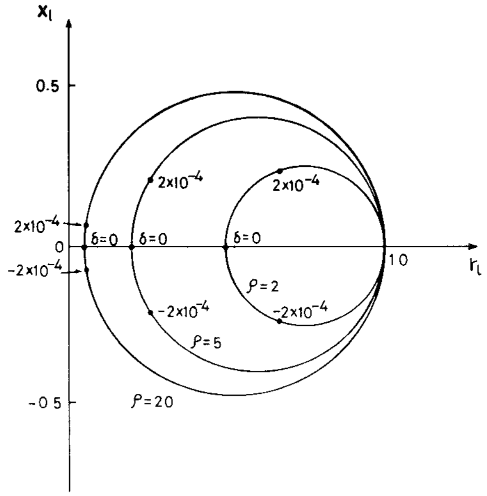

Fig. 4. Load impedance locus for various VSWR ($Q_0=3500$, $l=\lambda g_0/4$).

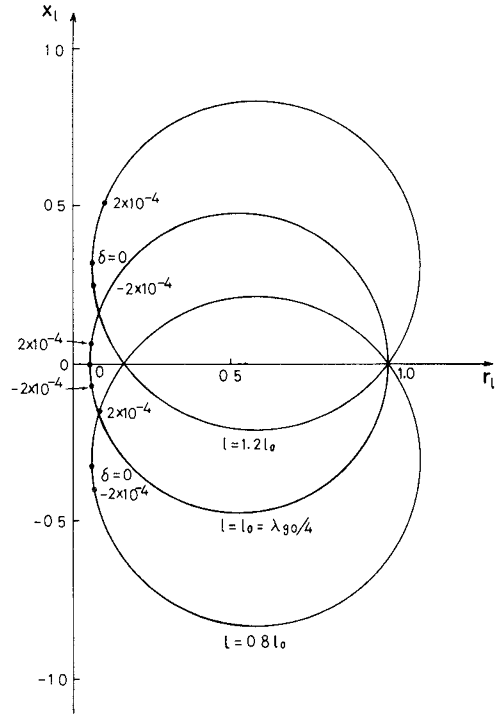

Fig. 5. Load impedance locus for various line lengths ($Q_0=3500$, $\rho=20$).

resonant frequency f_0 is a decreasing function of x [10], the load impedance can be controlled by d, l, and x.

The approximate oscillation frequency is obtained as follows. From (1), we obtain the approximate load reactance:

$$x_l \simeq \frac{(\rho-1)[2Q_0\delta+(\pi/2)(\rho+1)\eta]}{\rho^2+(2Q_0\delta)^2} \tag{7}$$

where

$$\eta=\frac{f-f_l}{f_l}. \tag{8}$$

The f_l denotes the frequency corresponding to $\lambda g=4l$. The oscillation frequency is determined by

$$x_l+x_d=0. \tag{9}$$

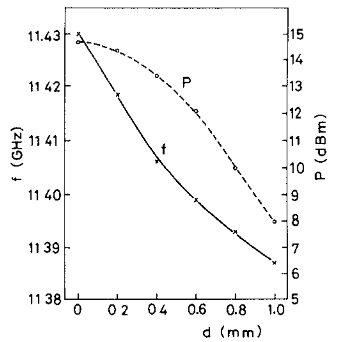

Fig. 6. Oscillating characteristics as a function of the distance between resonator and microstripline edge ($l=2.4$ mm, $V_d=7.5$ V).

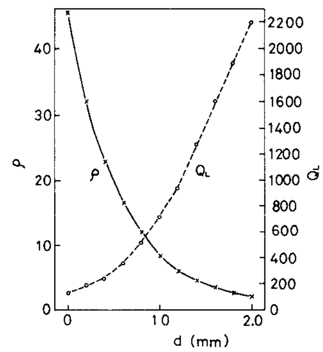

Fig. 7. VSWR ρ and loaded quality-factor Q_L of a resonator as a function of the distance between resonator edge and microstripline edge.

Provided the frequency dependence of x_d can be neglected compared with that of x_l, the oscillation frequency is determined in a good approximation by setting $x_l=0$, and is given by

$$f=f_0\left[1-\frac{(\rho+1)\pi}{4Q_0}\eta\right]. \tag{10}$$

IV. Oscillating Characteristics

A. The Characteristics Controlled by d

The oscillation frequency and output power are shown as functions of d in Fig. 6, when $l=2.4$ mm, $f_0=11.43$ GHz ($\lambda g_0 \simeq 10$ mm), and the bias voltage $V_d=7.5$ V. The maximum output power is obtained when $d=0$. The variation of P is about 0.3 dB for the change of d from 0 to 0.2 mm. The variation of f is about 12 MHz for the same change of d. The dependencies of ρ and the loaded quality-factor Q_L of the dielectric resonator on d, are shown in Fig. 7. The accuracy of d is less than ± 0.1 mm. The characteristics of the dielectric resonator used are listed in Table I.

B. The Characteristics Controlled by l

The oscillation frequency and output power are shown as functions of l in Fig. 8, when $d=0$, $f_0=11.43$ GHz, and $V_d=7.5$ V. The output power is maximized when l is about 2.4 mm. In the vicinity of the maximum output power point the changing rate of oscillation frequency is about 7.5 MHz for the change 0.2 mm of l. The accuracy of l is less than ± 0.1 mm.

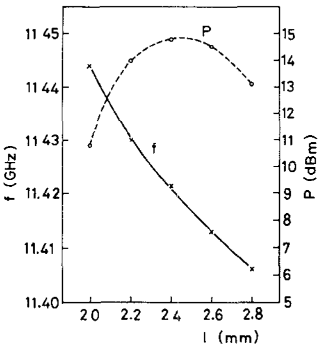

Fig. 8. Oscillating characteristics as a function of the resonator center position ($d=0$, $v_d=7.5$ V).

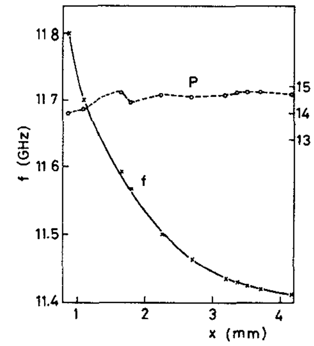

Fig. 9. Oscillating characteristics as a function of air gap thickness ($l=2.4$ mm, $d=0$, $v_d=7.5$ V).

TABLE I
CHARACTERISTICS OF THE DIELECTRIC RESONATOR

Diameter	5.0 mm
Height	2.0 mm
Unloaded Q	3500
Relative dielectric constant	38
Temperature coefficient of the resonant frequency	18 ppm/°C

C. The Characteristics Controlled by x

The oscillation frequency and output power are shown as functions of x in Fig. 9, when the resonant frequency f_0 is changed by changing x on the condition that $V_d=7.5$ V, $d=0$, and $l=2.4$ mm. The output-power variation is less than 1 dB over the whole frequency change. The tuning range is about 400 MHz with x varied from 0 to 3 mm.

D. Bias Dependency

The oscillation characteristics as a function of bias voltage V_d are shown in Fig. 10, where l is taken as a parameter. It is seen that, as l decreases, the change of oscillation frequency due to the change of bias voltage becomes smaller, that the range of the bias voltage within which the oscillation is possible becomes wider, and that the bias voltage at which the output power is maximized becomes higher.

E. Bias Pushing Figure

The bias pushing figure is shown as a function of l and d in Fig. 11, when f_0 is 11.43 GHz for $d=0$ and $l=2.4$ mm.

V. Frequency Stabilization with Temperature

A. Temperature Dependence of Oscillation Frequency

The temperature dependence of oscillation frequency is determined by that of Gunn diode parameters and that of the resonant circuit. Though the temperature dependence of a Gunn diode itself can be expressed by that of a large-signal susceptance [11], we regard, for simplicity, the diode reactance x_d in Fig. 2 as a basic temperature dependent factor. Denoting by f_{00} the resonant frequency of the dielectric resonator at ambient temperature T_0, and using (10), we can write the approximate oscillation frequency

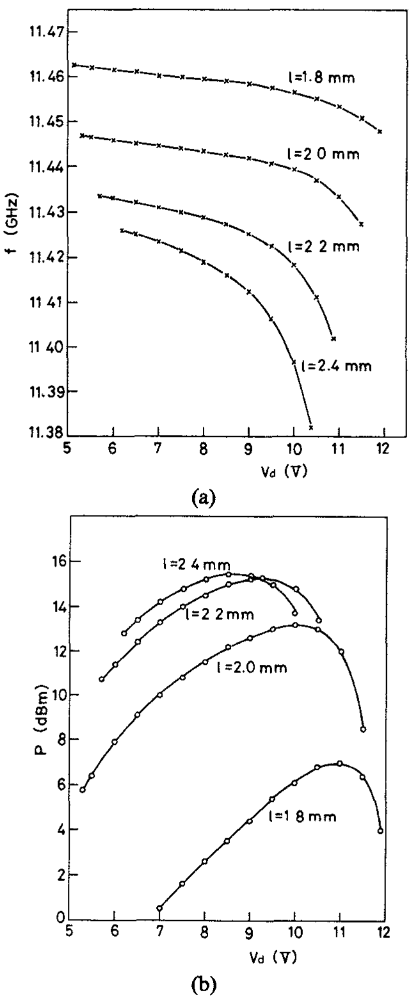

Fig. 10. Oscillating characteristics as a function of the bias voltage for $d=0$. (a) Oscillation frequency. (b) Output power.

f_{T_0} at T_0 as

$$f_{T_0}=f_{00}\left[1-\frac{(\rho+1)\pi}{4Q_0}\eta_0\right] \tag{11}$$

where

$$\eta_0=\frac{f_{00}-f_l}{f_l}. \tag{12}$$

If x_d is changed from 0 to Δx_d, and f_0 is changed from f_{00}

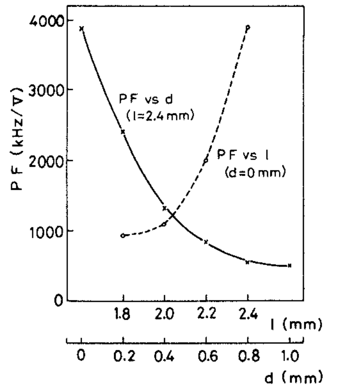

Fig. 11. Bias pushing figures (P. F.) as functions of d and l.

to $f_{00}+\Delta f_0$ due to the change of temperature ΔT, then the change of oscillation frequency Δf_T due to ΔT is approximated by, from (7) and (9),

$$\frac{1}{f_{T_0}}\frac{\Delta f_T}{\Delta T}=\frac{1}{f_{00}}\frac{\Delta f_0}{\Delta T}-\frac{1}{f_{T_0}}\frac{\Delta f_d}{\Delta T} \tag{13}$$

where

$$\frac{\Delta f_d}{\Delta T}\equiv\frac{F(\rho)f_{00}}{Q_0}\left[1+\left(\frac{\rho+1}{\rho}\right)^2\frac{\pi^2}{4}\eta_0^2\right]\frac{\Delta x_d}{\Delta T} \tag{14}$$

$$F(\rho)=\frac{\rho^2}{2(\rho-1)}. \tag{15}$$

If the change of the resonant frequency Δf_0 is zero, then $\Delta f_T=-\Delta f_d$. Therefore, it is expected that the frequency stability is improved by reducing Δf_d. Under the constant Q_0 condition, the value of Δf_d is minimized when $\rho=2$ and $\eta_0=0$, since $F(\rho)_{\min}=2$ ($\rho=2$). To reduce Δf_d for the fixed values of ρ and η_0, it is required to reduce Δx_d and to increase Q_0. However, it is difficult to reduce Δx_d by means of circuit technology because Δx_d depends mainly on the diode itself, and there is a limit in increasing Q_0. In the circumstances, in order to obtain the high stability, we have adopted a method to cancel the first and second terms of (13) by using a dielectric resonator of positive temperature coefficient.

B. Frequency Stabilization with Temperature

The dielectric material used for the resonator is new low-loss ceramics developed in the Matsushita Material Research Laboratory, Osaka, Japan [12]. It consists of $Ba[Zn_{1/3}Nb_{2/3}]O_3$—$Ba[Zn_{1/3}Ta_{2/3}]O_3$ solid-solution system. At X band, the relative dielectric constant is 30–40, and the unloaded Q value of the dielectric resonator is 5000~7000 (measured in a waveguide). The temperature coefficient of the resonant frequency can be changed continuously within the range from 0 to 30 ppm/°C.

The temperature characteristics of the oscillator are shown in Fig. 12. The four curves correspond to the different values of air gap thickness x in Fig. 1, while $d=0$ and $l=2.6$ mm are kept constant. From Fig. 12, we find the facts that the curvature of the frequency variation

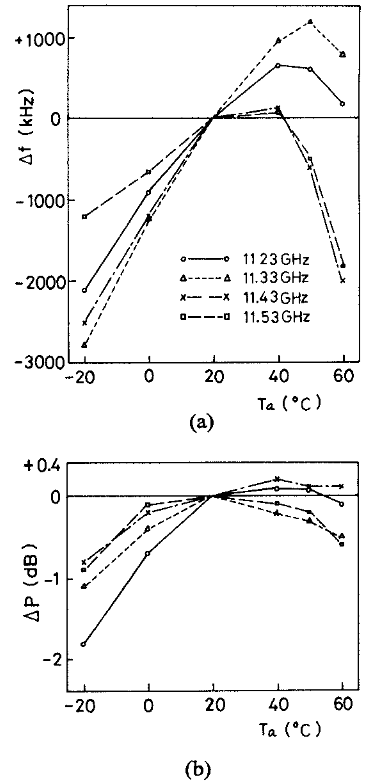

Fig. 12. Dependence of the temperature characteristics on the center frequencies ($l=2.6$ mm, $d=0$, $v_d=8.0$ V). (a) Frequency deviation. (b) Power deviation.

increases in the higher temperature range, and that this tendency becomes larger as the central frequency becomes higher. The main reasons for these facts may be the following three.

1) The property of a Gunn diode itself: the former fact is mainly due to the property that $\Delta x_d/\Delta T$ in (14) becomes larger with increasing temperature as a general property of a Gunn diode itself so that $\Delta f_d/\Delta T$ becomes large [11].

2) The effect of position of the dielectric resonator: the latter fact is mainly due to the property that η_0 in (14) increases as the central frequency f_{00} increases (this is equivalent to the increase of l), so that $\Delta f_d/\Delta T$ becomes large.

3) The change of ρ and Q_0 is also regarded as the reason that ρ and Q_0 will change so as to make $\Delta f_d/\Delta T$ large, with increasing the temperature or the central frequency.

The temperature characteristics of the oscillator are shown in Fig. 13 for $d=1.0$ mm and $l=2.6$ mm, when the central frequency is chosen to be 11.23 GHz. The unloaded Q value of the dielectric resonator was about 3500 (on an alumina substrate), and the temperature coefficient of the resonant frequency was about 5 ppm/°C. In this case, the two terms in the right-hand side of (13) have been almost cancelled so that the frequency variation is less than ±100 kHz over the temperature range from −20 to 60°C at the bias voltage of 8.0 V. The bias pushing

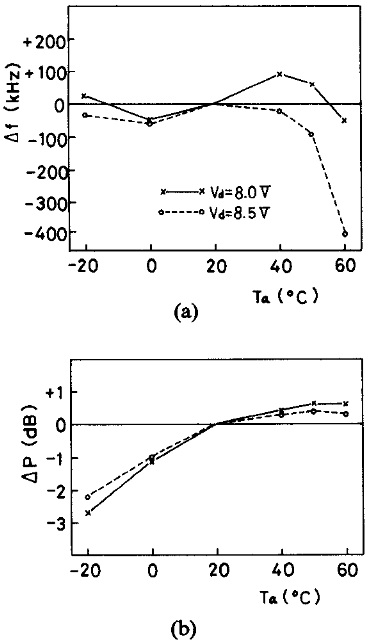

Fig. 13. Temperature characteristics of a highly stabilized oscillator ($l=2.6$ mm, $d=1.0$ mm). (a) Frequency deviation. (b) Power deviation.

figure is about 600 kHz/V, and the pulling figure is about 700 kHz. The output power is 8.4 dBm at the temperature of 20°C with V_d fixed at 8.0 V.

VI. Conclusion

An MIC Gunn oscillator of a simple structure using a dielectric resonator was studied. The relation of the oscillating characteristics with the coupling position of the dielectric resonator was investigated, and it was clarified how the oscillating characteristics could be controlled by several circuit parameters. As a result, it has been shown that the oscillating characteristics change sensitively according to the change of several parameters, and that the considerable accuracy is required to obtain the desired characteristics in an MIC oscillator of a simple structure, such as studied in this paper.

The factors affecting the frequency stability with temperature have also been studied, and it has been shown that the circuit condition also contributes to it considerably though the characteristic of the frequency variation with temperature results basically from the property of a Gunn diode itself. Based on these investigations, the temperature stability was optimized, and the high frequency stability of less than ±100 kHz over the temperature range from −20 to 60°C was realized by using a newly developed low-loss dielectric resonator.

Acknowledgment

The authors wish to express their sincere gratitude to Dr. Y. Iida, Dr. R. Sasaki, Dr. A. Oyama, and H. Ohyama for their helpful guidances. The authors are also indebted to Dr. H. Ouchi and S. Kawashima of Matsushita Material Research Laboratory for the development of the dielectric resonators, and to Dr. M. Nakajima of Kyoto University, Kyoto, Japan, for his helpful advice for the preparation of this paper. Thanks are also due to H. Kitazaki who supplied the substrate with the conductive strip, and to T. Uwano who examined the measurement techniques.

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