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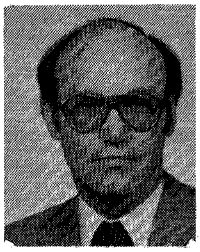

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Hold-In Characteristics of an Extended Range Gunn Oscillator System

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Abstract —**This paper describes a new Gunn oscillator system having an additional arrangement for controlling the instantaneous frequency of the oscillator through an automatic frequency control circuit. By utilizing this new technique, based upon the principle of self tracking, the locking bandwidth of an injection-locked Gunn oscillator can be increased to a large extent without affecting its stability. Experimental observations are found to be in good agreement with the conclusions of the analytical approach.**

I. Introduction

IN THE LAST several years, quite a lot of work has been done on the various aspects of an injection-locked Gunn oscillator. As a result, it has been shown that an attempt to increase the locking bandwidth of an injection-locked Gunn oscillator by increasing the strength of the incoming signal is always accompanied by the manifestation of an asymmetric character of the locking bandwidth, i.e., the hold-in ranges on the two sides of the center frequency of the oscillator become different [1], [2]. Moreover, it is not always possible to increase the strength of the synchronizing signal. On the contrary, the strength of the synchronizing signal is usually low. Therefore, the purpose of this paper will be to develop an injection-synchronized Gunn oscillator system that will have a much wider bandwidth than that of an ordinary injection-locked Gunn oscillator, even if the strength of the incoming signal is low. It is also shown that in the proposed system the asymmetric nature of the locking characteristic can be reduced to a great extent. This will be demonstrated both theoretically and experimentally in the sections to follow.

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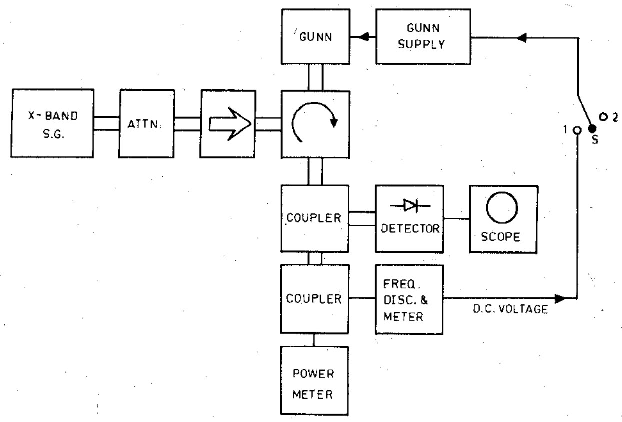

Fig. 1. Schematic representation of the proposed system.

II. Description of the System

The proposed Gunn oscillator system is shown in Fig. 1. It is basically a dual control system consisting of a Gunn oscillator, a frequency discriminator, and an arrangement for controlling the Gunn bias. The output of the Gunn oscillator is fed to the frequency discriminator, the output of which in turn controls the instantaneous frequency and amplitude of the Gunn oscillator through the variation of the bias voltage.

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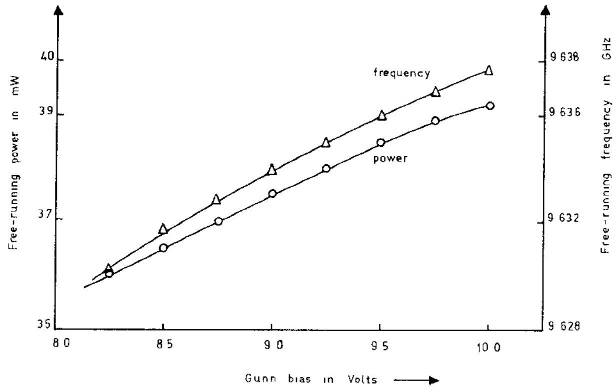

Fig. 2. Experimental dependence of power and frequency of a Gunn oscillator (manufactured by M/s Electronics Corporation India Ltd, Model 480B) using the Gunn diode manufactured by Microwave Associates, No: MA-49104.

III. Physics of the System Behavior

In order to be able to understand the mechanism of its operation, let us first refer to the experimental results of Fig. 2, which indicates the dependence of the power and frequency of a free-running oscillator on the Gunn bias. Observe that, in general, both the frequency and the power of the oscillator increase with the Gunn bias voltage in a nonlinear fashion. However, a region can be identified where the variations are fairly linear.

Assume that the free-running frequency of the oscillator is tuned to the center frequency of the frequency discriminator. Let us now inject a signal, having a frequency equal to that of the free-running oscillator, into the system. One easily finds that the output of the discriminator will have a zero potential in such a situation. Now, if the frequency of the synchronizing signal is increased, the frequency of the local oscillator will also be increased. This increase of frequency of the local oscillator will develop a positive dc potential at the output of the discriminator. This dc potential will increase the frequency of the local oscillator through the variation of the Gunn bias. This increase in frequency of the local oscillator due to increase of the Gunn bias effectively reduces the open-loop frequency error. Note that increase of the Gunn bias also increases the amplitude of the local oscillator. This increase of oscillator amplitude will have a tendency to decrease the pulling force on the oscillator due to the external signal. Whereas, if the frequency of the synchronizing signal is decreased from that of the free-running oscillator, the negative dc output of the frequency discriminator will not only decrease the frequency of the oscillator but will also reduce the amplitude of the oscillator itself. Thus, the pulling force of the synchronizing signal, when it is on the lower side, will be stronger than when it is on the upper side of the center frequency. As a consequence, it is expected that the lower side lock range of the Gunn oscillator system will be greater than that of the upper side. Hence, in injection-locked Gunn oscillators where the upper side lock range is greater, this method will reduce the asymmetric nature of the locking characteristics.

Thus, one concludes that by controlling the bias voltage of the oscillator in correspondence to a measure of the instantaneous frequency difference between the local oscillator and the synchronizing signal, not only the locking range of the oscillator will be increased but also the asymmetric hold-in characteristics of the injection-locked Gunn oscillator will be reduced. As a matter of fact, a judicious control of the Gunn bias can equalize the hold-in range on the two sides of the center frequency of the oscillator.

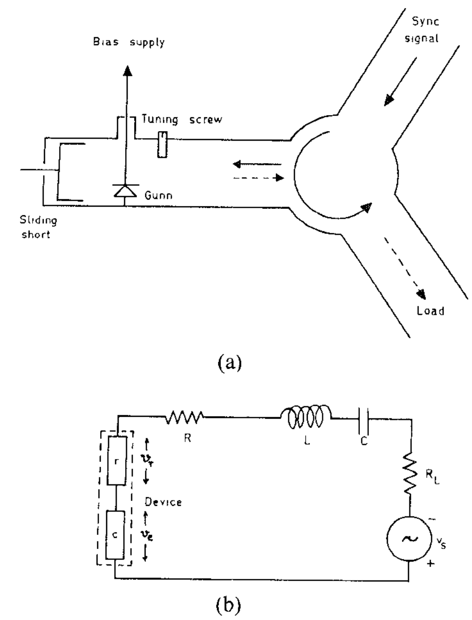

Fig. 3. (a) A typical arrangement of a Gunn oscillator with the provision of injection locking. (b) Analytical equivalent representation of Fig. 3(a).

IV. Analytical Approach

The typical arrangement of a Gunn oscillator with the provision of injection locking is shown in Fig. 3(a). The analytical equivalent representation [3] of Fig. 3(a) is shown in Fig. 3(b). $v_r(i)$ is the voltage drop across the nonlinear device resistance (r), and $v_c(i)$ denotes the same across the nonlinear device capacitance (c). $v_r(i)$ and $v_c(i)$ have been assumed to be of the forms [4], [5]

$$v_r(i) = -\beta_1 i + \beta_2 i^2 + \beta_3 i^3 \tag{1}$$

and

$$v_c(i) = \alpha_1 q + \alpha_2 q^2 + \alpha_3 q^3 \tag{2}$$

where

$$i = \frac{dq}{dt} \tag{3}$$

and α_j and β_j ($j = 1,2,3$) are constants of the nonlinear active device. Using (1)–(3), one can write an oscillator equation in the presence of the synchronizing signal $v_s(t)$ as

$$\frac{d^2q}{dt^2} + \frac{\omega_r}{Q_L}\left[-r_1\dot{q} + b_2\dot{q}^2 + b_3\dot{q}^3 + a_2q^2 + a_3q^3\right] + \omega_r^2(1 + C\alpha_1)q = \frac{\omega_r^2}{Q_L}q_s(t) \tag{4}$$

where

$$q_s = \frac{Q_L}{\omega_r^2 L} \cdot v_s \quad (5)$$

$$r_1 = \frac{\beta_1 - R - R_L}{R_L} \quad (6)$$

$$Q_L = \frac{\omega_r L}{R_L}, \quad a_h = \frac{\alpha_h}{R_L}, \quad b_h = \frac{\beta_h}{R_L} \qquad (h = 2 \,\&\, 3) \quad (7)$$

and $\omega_r (= 1/\sqrt{LC})$ is the resonant frequency of the cavity. Note that R, L, and C are the equivalent lumped circuit elements of the resonator. R_L is the load resistance.

The locking behavior of the oscillator can be determined by solving (4). But it is not possible to obtain an exact solution of (4) due to its highly nonlinear character. Therefore, in the following section, the usual techniques of nonlinear mechanics will be applied.

A. Free-running Behavior of the Oscillator

Before going into the theoretical analysis of a synchronized oscillator, let us very briefly refer to the free-running characteristic of the oscillator. The equation describing a free-running oscillator is given by

$$\frac{d^2 q_0}{dt^2} + \frac{\omega_r}{Q_L}\left[-r_1 \dot{q}_0 + b_2 \dot{q}_0^2 + b_3 \dot{q}_0^3 + a_2 q_0^2 + a_3 q_0^3\right] + \omega_r^2 (1 + C\alpha_1) q_0 = 0. \quad (8)$$

Note that q_0 denotes the value of q at the free-running state of the oscillator.

Assuming the solution of (8) as

$$q_0(t) = A_0(t) \cos(\omega_0 t + \Psi_0) \quad (9)$$

and applying the method of harmonic balance to (8), one obtains the following relations:

$$\frac{dA_0}{dt} = \frac{\omega_r}{2Q_L}\left(r_1 - \frac{3}{4} b_3 \omega_0^2 A_0^2\right) A_0 \quad (10)$$

and

$$-\frac{d\Psi_0}{dt} = \frac{\omega_r}{2}\left(\frac{\omega_0}{\omega_r} - \frac{\omega_r}{\omega_0}(1 + C\alpha_1)\right) - \frac{3}{8}\frac{\omega_r a_3}{Q_L} A_0^2. \quad (11)$$

It is interesting to note that r_1 represents the normalized net negative resistance of the circuit, whereas b_3 gives the reduction in the normalized resistance at the fundamental frequency as a function of current amplitude. Likewise, the factor $1 + C\alpha_1$ can be interpreted as the normalized change in net susceptance due to electronic tuning.[1] At the steady-state of operation (10) and (11) reduce to the following forms:

$$A_0^2 = \frac{4}{3 b_3 \omega_0^2} r_1 \quad (12)$$

and

$$\omega_0^2 \simeq \omega_r^2 (1 + C\alpha_1)\left(1 + \frac{3 a_3 \omega_0}{4 Q_L \omega_r} A_0^2\right). \quad (13)$$

[1] This is incorporated from the suggestion of the anonymous reviewer.

The free-running output power of the oscillator is given by

$$P_0 = \frac{4 R_L}{3 b_3} r_1. \quad (14)$$

Since the value of Q_L is fairly large in practice, the free-running frequency (ω_0) of the oscillator approximates to [cf. (13)]

$$\omega_0^2 = \omega_r^2 (1 + C\alpha_1). \quad (15)$$

It appears from (14) that an increase in the free-running power means an increase in the value of r_1, because the other parameter (b_3) is due to the higher order nonlinear term. Similarly, a look at (15) indicates that $(1 + C\alpha_1)$ changes with the bias supply.

B. Locking Behavior in the Presence of an External Signal

Let us consider Fig. 1 and keep the switch S in position 2. In such a case, the oscillator operates under the influence of an external signal but without the influence of bias modulation. Analytical behavior of the oscillator under this situation may be described by (4).

The synchronizing signal is taken to be of the form

$$q_s = -Q_s \sin \omega_1 t \quad (16)$$

the angular frequency (ω_1) of the injecting signal is assumed to be close to the free-running frequency (ω_0) of the oscillator, such that synchronism, if desired, can be established between the external signal and the oscillator. In such a situation, one assumes the solution of (4) as

$$q(t) = A(t) \cos(\omega_1 t + \Psi(t)). \quad (17)$$

Substituting this value of q in (4) and utilizing the method of harmonic balance, one obtains the following equations governing the instantaneous amplitude and phase of the oscillator:

$$\frac{dA}{dt} = \frac{\omega_r}{2Q_L}\left[r_1 - \frac{3}{4} b_3 \omega_1^2 A^2\right] A^2 + \frac{Q_s \omega_r^2}{2\omega_1 Q_L} \cos\Psi \quad (18)$$

and

$$-\frac{d\Psi}{dt} = \frac{\omega_r}{2}\left(\frac{\omega_1}{\omega_r} - \frac{\omega_r}{\omega_1}(1 + C\alpha_1)\right) - \frac{3\omega_r a_3}{8 Q_L} A^2 + \frac{Q_s \omega_r^2}{2\omega_1 Q_L A} \sin\Psi. \quad (19)$$

The locking characteristics of an oscillator can be determined with the help of the above two equations ((18) and (19)).

C. Synchronization Behavior in the Presence of Bias Control

Let us put the switch S of Fig. 1 in position 1. In this situation, the output of the frequency discriminator changes the bias voltage of the oscillator in accordance with the frequency difference between the synchronizing signal and the free-running oscillator. This change in bias voltage, in turn, modulates the amplitude and frequency of the oscillator.

Now referring to Section IV-A, one finds that the values of the nonlinear constants r_1 and α_1 of the active device change with the change of the Gunn bias [cf. (14) and (15)]. Therefore, one may write

$$r_{lc} = r_1\left[1+\frac{\mu_d}{r_1}\left(\omega_1+\frac{d\Psi}{dt}-\omega_0\right)\right] \tag{20}$$

and

$$(1+C\alpha_1)_c = (1+C\alpha_1)\left[1+2\frac{\mu_d}{1+C\alpha_1}\left(\omega_1+\frac{d\Psi}{dt}-\omega_0\right)\right] \tag{21}$$

where μ_d is the sensitivity of the frequency discriminator, and the symbols with subscript c denote the corresponding values of r_1 and α_1 under the influence of a control voltage. Substituting

$$y=\frac{\omega_1}{\omega_r},\quad y_0=\frac{\omega_0}{\omega_r},\quad m_2=\frac{\mu_d}{r_1}\omega_r$$

$$m_1 = 2\frac{\mu_d}{1+C\alpha_1}\omega_r,\quad T=\frac{\omega_r t}{2} \tag{22}$$

and using (20), (21), and (4), one finds that the equation describing the oscillator behavior can now be written as

$$\frac{d^2q}{dt^2}+\frac{\omega_r}{Q_L}\left[-r_1\left\{1+m_1\left(y-y_0+\frac{1}{2}\frac{d\Psi}{dT}\right)\right\}\dot{q} + b_2\dot{q}^2+b_3\dot{q}^3+a_2q^2+a_3q^3\right] + \left[1+m_1\left\{\left(y-y_0+\frac{1}{2}\frac{d\Psi}{dT}\right)\right\}\right]\omega_r^2(1+C\alpha_1)q = \frac{\omega_r^2}{Q_L}q_s. \tag{23}$$

Taking the external signal q_s in the form as (16) and assuming the solution of q in the form of (17), one can easily obtain the following equations [cf. (18) and (19)]:

$$\frac{da}{dT}+\frac{r_1 m_2}{2Q_L}\cdot\frac{d\varphi}{dT} = \frac{r_1}{Q_L}\left[1+m_2(y-y_0)-a^2y^2\right]a + \frac{F_i}{yQ_L}\cos\varphi \tag{24}$$

and

$$\frac{d\varphi}{dT}\left[1-\frac{m_1}{2y}(1+C\alpha_1)\right] = y-\frac{1+C\alpha_1}{y}\left[1+m_1(y-y_0)\right] - \frac{3na^2}{4Q_Ly}-\frac{F_i}{yQ_La}\sin\varphi \tag{25}$$

where

$$a=\frac{A}{A_f},\quad A_f^2=\frac{4r_1}{3b_3\omega_r^2},\quad n=\frac{a_3A_f^2}{\omega_r},\quad \varphi=-\Psi. \tag{26}$$

It may be noted that φ represents the phase difference between the oscillator output and the synchronizing signal.

1) *Frequency Response Characteristic*: In the steady-state (i.e., when $da/dT=0$ and $d\varphi/dT=0$) one obtains from (24) and (25) the following relations:

$$\frac{r_1}{Q_L}\left[1+m_2(y-y_0)-a_s^2y^2\right] = -\frac{F_i}{yQ_La_s}\cos\varphi_s \tag{27}$$

and

$$y-\frac{E}{y}-D=\frac{F_i}{yQ_La_s}\sin\varphi_s \tag{28}$$

where

$$E=(1+C\alpha_1)(1-m_1y_0)+\frac{3n}{4Q_L}a_s^2 \tag{29}$$

$$D=(1+C\alpha_1)m_1 \tag{30}$$

and the subscript s denotes the corresponding values of a and φ at the steady-state. Therefore, the frequency response characteristic of the synchronized oscillator can be had from the following relation:

$$\left(y-\frac{E}{y}-D\right)=\pm\frac{1}{Q_L}\left[\left(\frac{F_i}{ya_s}\right)^2 - r_1^2\left\{1+m_2(y-y_0)-a_s^2y^2\right\}^2\right]^{1/2} \tag{31}$$

where the plus or minus sign is to be taken depending on whether $\omega_1>\omega_0$ or $\omega_1<\omega_0$, respectively.

2) *Stability and Locking Range Characteristics*: Let us remember that all the steady-state amplitudes of the synchronized oscillator may not be stable. Or in other words, unless the frequency response characteristic of the injection synchronized oscillator is accompanied by the stability boundary one cannot conclude anything on the merit of the proposed system [6], [7]. Thus, in the following, we will examine the stability criteria of the oscillator by the method of Liapounov. In such a case, the characteristic equation, which gives the stability zones, is given by

$$\begin{vmatrix}(s-c_{11}) & (c_1-c_{12}-s)\\ -c_{21} & (c_2s-c_{22})\end{vmatrix}=0 \tag{32}$$

where

$$c_{11}=\frac{r_1}{Q_L}\left[1+m_2(y-y_0)-3a_s^2y^2\right]$$

$$c_{12}=-a_s\left(y-\frac{E}{y}-D\right)$$

$$c_{21}=\frac{1}{a_s}\left(y-\frac{E}{y}-D\right)-\frac{3n}{2Q_Ly}a_s^2$$

$$c_{22}=\frac{r_1}{Q_L}\left[1+m_2(y-y_0)-a_s^2y^2\right]$$

$$c_1=\frac{r_1m_2}{2Q_L},\quad c_2=1-\frac{m_1}{2y}(1+C\alpha_1)$$

and s is the complex frequency variable. Rewriting the characteristic equation as

$$c_2s^2-s(c_{22}+c_{11}c_2-c_1c_{21})+c_{11}c_{22}-c_{12}c_{21}=0$$

one finds that the stability conditions of the synchronized oscillator are given by

$$c_2\geqslant 0 \tag{33a}$$

$$c_{21}c_1-c_{22}-c_{11}c_2\geqslant 0 \tag{33b}$$

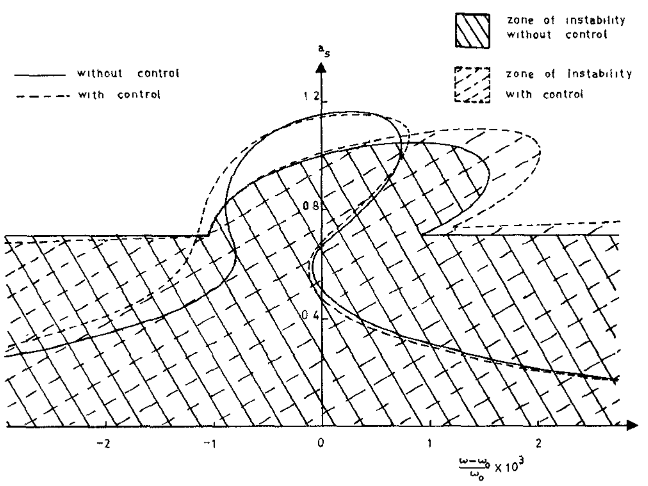

Fig. 4. Frequency response characteristics and the zone of stability of a synchronized oscillator with and without use of the bias control arrangement. $r_1 = 1.0$, $Q_L = 275$, $C\alpha_1 = 0$, $n = 0.533$, $F_i = 0.4$. Curve ----- with control $m_1 = 0.15$, $m_2 = 75$. Curve —— without control.

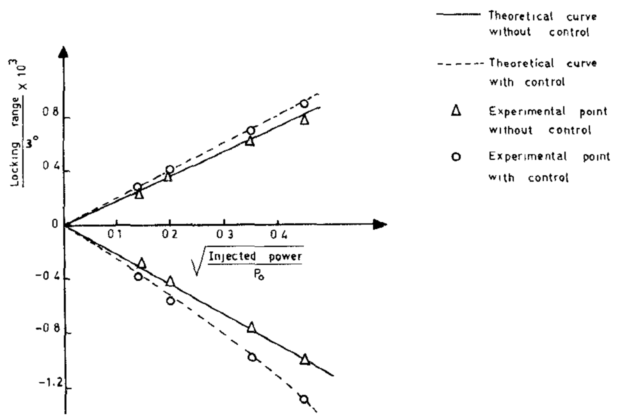

Fig. 5. Variation of locking range of a synchronized oscillator with and without use of the bias-control arrangement. (Gunn oscillator model no. ECIL 480B, sr. no. 0902). Oscillator free-running frequency = 9.636 GHz and free-running power = 37 mW. Theoretical parameters are $r_1 = 1.0$, $Q_L = 275$, $C\alpha_1 = 0$, $n = 0.533$.

and

$$c_{11}c_{22} - c_{12}c_{21} \geqslant 0. \tag{33c}$$

The frequency response characteristic and the zone of stability (determined by (33a), (33b), and (33c)) have been determined by adopting the method of numerical analysis via a digital computer. The results are shown in Fig. 4. This figure compares the zone of stability of the synchronized oscillator with and without the use of the bias-control arrangement. Note that the behavior of the oscillator within the zone of instability is unstable.

The lock-range of the oscillator gives a measure of the maximum frequency difference between the synchronizing signal and the free-running oscillator up to which synchronism is maintained. The difference of frequencies between the upper side lock point and the free-running frequency of the oscillator is said to be the upper side locking range, whereas the band below the free-running frequency is the lower side locking range. The extremum lock-points are theoretically determined with the help of Fig. 4. These are

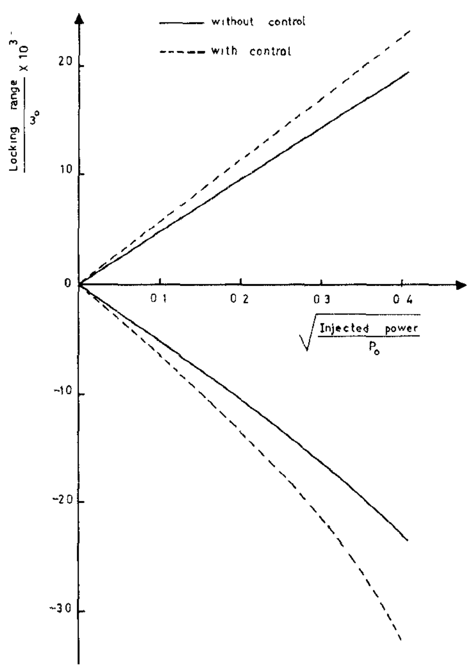

Fig. 6. Theoretical variation of locking range of the Gunn oscillator with the strength of the synchronizing signal. $r_1 = 1$, $Q_L = 10$, $C\alpha_1 = 0$, $n = 0.533$.

obtained by noting the maximum initial frequency offset of the synchronizing signal with respect to the free-running frequency of the oscillator but maintaining the conditions for stability. The results are shown in Fig. 5. Theoretical results, depicting the variation of the locking range with the strength of the synchronizing signal, are also shown in Fig. 6. As expected, this figure shows that a considerable increase in the locking range occurs by lowering the Q-value of the resonator.

V. Experiment

Detailed experimental observations on the proposed system of Fig. 1 have been carried out. The lock range has been experimentally determined. These observations are shown in Fig. 5. Theoretical results are also shown in the figure. It is seen that the experimental results agree very closely with the theoretical graph.

VI. Conclusions

The proposed technique of controlling the bias of the Gunn oscillator increases the locking range. The theoretical approach presented in this paper clearly explains the observed facts.

Acknowledgment

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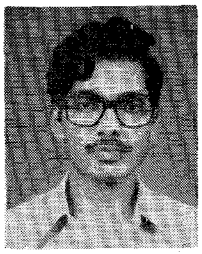

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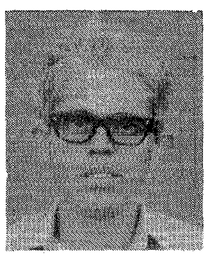

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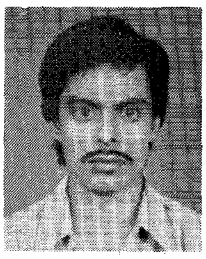

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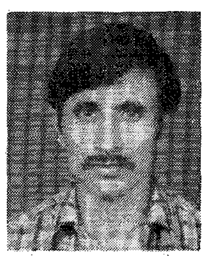

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He joined the Radionics Laboratory, Physics Department, Burdwan University in February 1981 as a Research Scholar. His research work centers around the study of solid-state microwave oscillations.