Unconditionally Stable Tracking Discriminator at 35 GHz

B. N. Biswas, *Member, IEEE,* A. P. Sinha, P. Lahiri, and D. Mondal, *Student Member, IEEE*

***Abstract*—A two-mode tuning method for injection locked oscillators at microwave frequencies has been presented. This technique allows one to modify the frequency response characteristics and stability boundary of an injection locked oscillator (ILO) in a favorable direction. Using this idea, a lock-in microwave discriminator has been proposed. The stability properties, tracking zone and other characteristics of the discriminator are presented based on both a mathematical analysis and experimental results.**

I. Introduction

QUITE a few activities in recent times have been observed in the area of microwave and mm-wave systems with particular emphasis on the realization of tracking receivers used in radars or other short range communication systems. Since there exists an atmospheric window of em waves at 35 GHz, transmitters and receivers are often designed at this frequency. So far as detection at this frequency-band is concerned, it is a standard practice to use a phase locked demodulator, as shown in Fig. 1(a), incorporating harmonic mixer and i.f. stages which introduce a time-delay in the system. The appearance of the time delay not only introduces distortion in the discriminator output but also causes the system to become susceptible to false or spurious locking. In view of this it is advisable to use an injection locked FM demodulator (Fig. 1(b)). Due to its circuit simplicity an injection locked FM discriminator does not have this false locking problem, but it is not unconditionally stable. The serious problem with the conventional injection locked mm-wave discriminator is its incapability of detecting a signal below a certain level because at low levels of input signal, the system becomes unstable. Therefore, in order to improve upon this, i.e., to enhance detection efficiency, we propose a novel injection locked detection technique which is easily realizable by introducing two modes of tuning the local oscillator. This is explained in the following sections.

II. System Configuration

The proposed system configuration is shown block diagramatically in Fig. 1(c). It consists of a waveguide tuned Gunn oscillator the free-running frequency of which is 34.8 GHz with an output power of 175 mW. It is injection synchronized with the input signal, frequency modulated by the information signal. The output of the oscillator is amplitude detected to recover the information. A fraction of the output is used to control the free-running frequency of the injection synchronized Gunn oscillator through varactor tuning. We call this arrangement as the Voltage Controlled Injection Locked Oscillator (VCILO). It may be recalled that use of a synchronous oscillator as a discriminator is often recommended because of its wide tracking bandwidth, excellent filtering property for noise rejection, fast acquisition, large amplification and high sensitivity to recover the signal buried in noise [1]–[3]. But it is often found that if the relative strength of the input signal is low the oscillator fails to lock on to the incoming signal hence detection becomes impossible. The ILO described in this paper is a unique free-running Gunn oscillator of Van der Pol type whose natural frequency can be changed and hence the pull-in range can be increased by means of varactor tuning, i.e., by means of reactance modulation on application of a dc voltage across the varactor terminals. Now referring to the analytical equivalent circuit of the oscillator as shown in Fig. 2, the governing equation of the system can be written as:

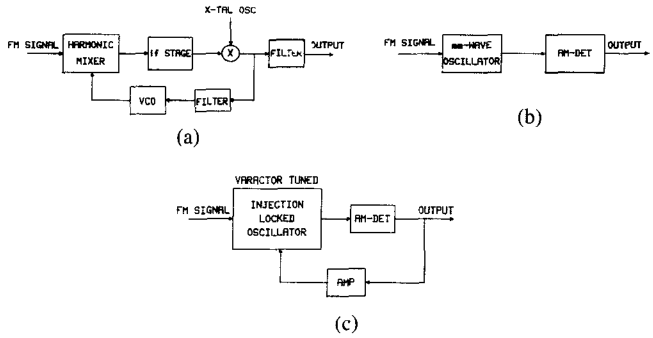


Fig. 1. (a) Block diagram of Phase Locked Discriminator. (b) Block diagram of Injection Locked Discriminator (ILD). (c) Schematic diagram of Varactor Tuned Injection Locked Discriminator (VTILD).

$$\frac{d^2v}{dt^2} + \frac{\omega_o}{Q}\frac{d}{dt}(-C_1v + C_3v^3) + \omega_o^2 v = \frac{I_s}{-QG}\omega_o\omega_c \sin(\omega_c t - \theta(t) \quad (1)$$

where

$$C_1 = \frac{\beta_1 - G}{G}; \quad C_3 = \frac{\beta_3}{G}$$

and

Q is the quality factor of the oscillator
G is the load conductance

Manuscript received March 9, 1992; revised July 21, 1992. This work was supported by the Department of Electronics, Government of India and the University Grants Commission.
The authors are with the Radionics Laboratory, Physics Department, Burdwan University, Burdwan 713 104 West Bengal, India.
IEEE Log Number 9205448.

0018-9480/93$03.00 © 1993 IEEE

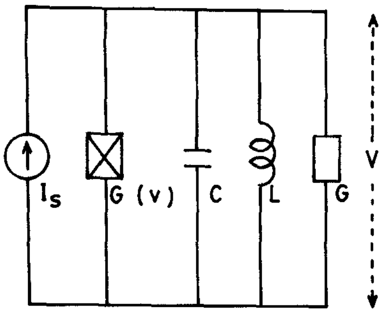


Fig. 2. Equivalent diagram of an Injection Locked Oscillator (ILO).

ω_o free-running frequency of the oscillator
ω_c frequency of the locking signal
$\theta(t)$ input modulation

Also note that β_1 and β_3 are the nonlinear constants of the device.

The output of the oscillator and the synchronizing signal are respectively taken as:

$$v(t) = A(t)\cos(\omega_c t + \psi(t)) \tag{2}$$

and

$$i_S(t) = I_S \cos(\omega_c t - \theta(t)) \tag{3}$$

where

$$\psi(t) = \psi_1(t) + \psi_2(t)$$

$\psi(t)$ Total phase of the locked oscillator with control
$\psi_1(t)$ Phase perturbation that corresponds to the sync. signal
$\psi_2(t)$ Phase perturbation due to varactor control, i.e.,

$$\frac{d\psi_2}{dt} = K|v|^2$$

where K is the sensitivity of varactor tuning.

Solving (1) with the help of (2) and (3), we obtain the amplitude and phase equations for the oscillator as:

$$\frac{da}{dt} = \frac{\omega_o}{2q}(1 - a^2)a + \frac{\omega_o}{2q}F\cos\phi \tag{4}$$

$$\frac{d\phi}{dt} = \Omega - \frac{\omega_o}{2q}\frac{F}{a}\sin\phi - Ka^2 + \frac{d\theta}{dt} \tag{5}$$

and

$$\Omega = \omega_c - \omega_o, \phi = \theta - \psi$$
$$= \theta - \psi_1 - \psi_2$$

with

$$a = \frac{A}{A_o}; \quad F = \frac{I_S}{C_1 A_o G};$$
$$A_o = \sqrt{\left(\frac{4C_1}{3C_3}\right)} \quad \text{and} \quad q = \frac{Q}{C_1}$$

Performing computational analysis of (4) and (5) it can be easily shown that both the amplitude and phase of the oscillator are modulated by the modulating signal. Thus the oscillator performs FM-AM conversion. Now the question is: how faithful is the conversion? To answer this, in the following we obtain the frequency response characteristic of the synchronized oscillator. In the steady state condition, the (4) and (5)

$$\frac{\omega_o}{2q}(1 - a_s^2)a_s + \frac{\omega_o}{2q}F\cos\phi_s = 0 \tag{6}$$

$$\Omega - \frac{\omega_o}{2q}\frac{F}{a_s}\sin\phi_s - Ka_s^2 = 0 \tag{7}$$

where a_s and ϕ_s are respectively the steady state values of 'a' and 'ϕ'. The modulation signal $\theta(t)$ has not been considered in writing (6) and (7). Defining the normalized control parameter $K_1 = 2qK/\omega_o$ and normalized frequency detuning $\Delta = (2q/\omega_o)\Omega$ and combining (6) and (7) we arrive at

$$(1 + K_1^2)a_s^6 - 2(1 + K_1\Delta)a_s^2$$
$$+ (1 + \Delta^2)a_s^2 - F^2 = 0 \tag{8}$$

Clearly (8) is a cubic equation in a_s^2 and plot of the positive real roots of a_s^2 give the frequency response curves for the oscillator for different strengths of the synchronizing signal. For the positive real roots of a_s^2 the entrainment is possible unless the roots are in the unstable zone. Once again the stability boundary for the oscillator [4] can be obtained from (4) and (5) by introducing arbitrarily small perturbations (u, v) in the oscillator amplitude and phase around its steady state values, i.e.,

$$a = a_s + u$$
$$\phi = \phi_s + v$$

Using these in the amplitude and phase equations, it is not difficult to set up the characteristic equation of the system, from which the stability condition can be shown to be given by

$$a_s^2 \geq \tfrac{1}{2} \tag{9}$$

$$3(1 + K_1^2)a_s^4 - 4(1 + K_1\Delta)a_s^2$$
$$+ 1 + \Delta^2 \geq 0 \tag{10}$$

Fig. 3 portrays the frequency response curves of the oscillators without control ($K_1 = 0$), along with the stability boundary. Here the important thing is that one has to make a suitable choice of the ratio of the synchronizing amplitude to that of the oscillator amplitude in relation to the frequency off set so as to have a linear conversion from FM to AM, as illustrated in Fig. 3. But when the strength of the synchronizing signal becomes low, the desired region creeps into the unstable region thus making the system unstable and a faithful detection is not at all possible in that case. Fig. 4 depicts the frequency response curve and the stability boundary of the varactor control ILO along with those of an ordinary ILO. Clearly the plots obtained reveal that not only the response characteristic for lower strength of the incoming signal becomes linear but also the unstable region has been pushed aside. So by controlling the frequency of the oscillator through varactor tuning, efficient frequency entrainment of the oscillator is possible even at very low values of the synchronizing amplitudes,

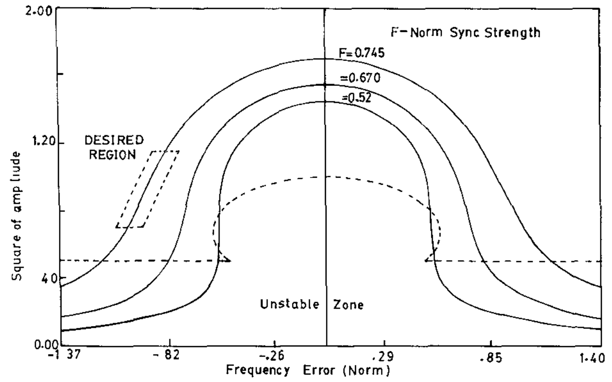


Fig. 3. Frequency response characteristics of an Injection Locked Oscillator along with the stability boundary.

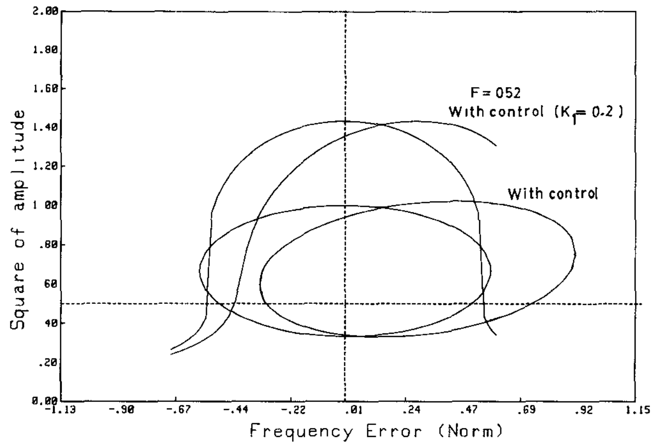


Fig. 4. Frequency response characteristic and stability boundary of a Voltage Controlled Injection Locked Oscillator (VCILO) and those of an ordinary ILO.

thus making the system unconditionally stable. Also from equation (10), we can easily calculate the angle of rotation of the stability ellipse when a control voltage is applied at the varactor terminal.

III. FM-AM Conversion

Ideal FM-AM conversion is possible only when the signal is passed through a differentiator. But a differentiator is known to enhance the noise level at its output. In order to avoid straight-forwarded differentiation, an ILO can be conveniently used to realize FM-AM conversion which can be easily understood from its frequency response characteristic [5]–[9]. Since an ILO is a tracking device, the noise falling outside the locking range will be automatically rejected by the ILO. As a result there will be considerable reduction of noise compared to an ordinary limiter discriminator. An efficient FM-AM converter should have high conversion efficiency, low harmonic distortion and the capability of handling a large-index FM signal. Minimum harmonic distortion at the output with the capability of handling a large-index FM signal demands a wideband linear zone in the frequency response curve. Injection synchronization alone is not suitable for this purpose as can be appreciated by referring to Fig. 3. The proposed discriminator using VCILO has a wide lock

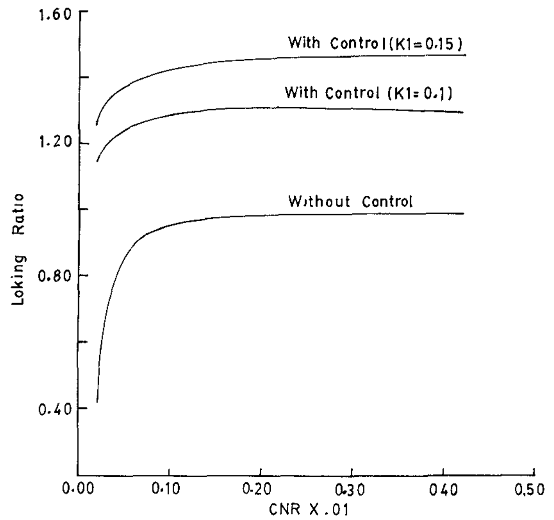


Fig. 5. Locking Ratio against CNR $\cdot$ C_1^2 (Without and with varactor control) $[C_1 = 0.1, F = 0.55]$.

range relative to an ordinary Injection Locked Discriminator (ILD) (as calculated in the following section and the result is shown in Fig. 5). Because of the large tracking zone, the chance of cycle slipping is considerably reduced. Moreover, because the frequency response characteristics of the varactor tuned ILO behave almost like an ideal frequency limiter for large frequency deviation, the FM-AM conversion is almost negligible due to large frequency deviation, which may sometimes appear due to the accompanying noise. From (8) we get

$$\frac{da^2}{d\Delta} = \frac{2a^4K_1 - 2\Delta a^2}{3a^4(1+K_1^2) - 4a^2(1+K_1\Delta) + 1 + \Delta^2}$$

For large values of K_1, it turns out as

$$\frac{da^2}{d\Delta} \cong \frac{2K_1}{3(1+K_1^2)}$$

which is independent of the frequency detuning (Δ). Thus it is seen that varactor control makes the response curve more linear than that of an ordinary ILO. So the VCILO can be used as an efficient FM-AM converter for large-index FM signal with low harmonic distortion.

IV. Oscillator Performance in Presence of Noise

The frequency stability of an oscillator is affected in the presence of noise [10]. An ILO has the property of reducing the deleterious effect of unwanted disturbances accompanying the signal i.e. interfering tones and additive noise [4], [11]. But for very low CNR, even ILO fails to track the signal. Here we shall study the performance of a varactor tuned ILO in presence of additive Gaussian noise (AGN). Since exact analysis when the CNR is low, is not possible, we analyze the behavior of the system in the high CNR case. Thus we take recourse to the technique of linearization of non-linear equation [12] remembering that it is not applicable for phase deviations comparable to $\pi/2$.

In presence of AGN the amplitude and phase equations of the VCILO are given by

$$\frac{da}{dt} = \frac{\omega_o}{2q}(1-a^2)a + \frac{\omega_o}{2q}F\cos\phi + \frac{\omega_o}{2q}\frac{n_1(t)}{C_1A_o} \tag{11}$$

$$\frac{d\phi}{dt} = \Omega - \frac{\omega_o}{2q}\frac{F}{a}\sin\phi - Ka^2 + \frac{\omega_o}{2qa}\frac{n_2(t)}{C_1A_o} \tag{12}$$

where $n_1(t)$ and $n_2(t)$ are independent, Gaussian noise terms with zero mean. In the present model we consider small phase and amplitude fluctuations from the steady state values, i.e.,

$$a(t) = a_s + a_p(t), \phi(t) = \phi_s + \beta(t)$$

Thus the equation for $a_p(t)$ and $\beta(t)$ are written as (cf. (11) and (12))

$$\frac{da_p}{dt} = \frac{\omega_o}{2q}(1-3a_s^2)a_p - \frac{\omega_o}{2q}F\sin\phi_s\beta + \frac{\omega_o n_1(t)}{2qC_1A_o}$$

$$\frac{d\beta}{dt} = -\frac{\omega_o}{2q}\frac{F}{a_s}\cos\phi_s\beta + \left(\frac{\omega_o}{2q}\frac{F}{a_s^2}\sin\phi_s - 2Ka_s\right)a_p + \frac{\omega_o n_2(t)}{2qC_1A_oa_s}$$

In Laplace notation (s being the Laplacian operator)

$$sa_p = -a_{11}a_p - a_{12}\beta + N_1(s) \tag{13}$$

$$s\beta = a_{21}a_p - a_{22}\beta + N_2(s) \tag{14}$$

where

$$s \equiv \frac{d}{dt},$$

$$a_{11} = \frac{\omega_o}{2q}(1-3a_s^2) = (-)ve \text{ quantity as } a_s^2 \geq 0.5$$

$$a_{12} = \frac{\omega_o}{2q}F\sin\phi_s,$$

$$a_{21} = \frac{\omega_o F}{2qa_s^2}\sin\phi_s - 2Ka_s,$$

$$a_{22} = \frac{\omega_o F}{2qa_s}\cos\phi_s$$

$$N_1(s) = \frac{\omega_o n_1(s)}{2qA_oC_1} \quad \text{and}$$

$$N_2(s) = \frac{\omega_o n_2(s)}{2qA_oC_1a_s}$$

Thus (13) and (14) can be expressed as

$$a_p = \frac{(s+a_{22})N_1(s) - a_{12}N_2(s)}{(s+a_{11})(s+a_{22}) + a_{12}a_{21}} \quad \text{and}$$

$$\beta = \frac{a_{12}N_1(s) + (s+a_{11})N_2(s)}{(s+a_{11})(s+a_{22}) + a_{12}a_{21}}$$

Now the amplitude and phase variance are defined as

$$\sigma_{a_p}^2 = \int_{-\infty}^{\infty} |a_p|^2\, d\omega \quad \text{and}$$

$$\sigma_\beta^2 = \int_{-\infty}^{\infty} |\beta|^2\, d\omega \tag{15}$$

Let us define the CNR as $A_o^2/N_o\Delta\omega$, where $\Delta\omega$ is the bandwidth of the input bandpass filter and N_o is the spectral density of $n_1(s)$ and $n_2(s)$. From (15) we get (16) and (17), which are shown at the bottom of the page, where

$$\Omega_1 = \frac{\omega_o F}{2qa_s}$$

To find the locking condition in presence of noise we put the average value of phase fluctuation to be zero

$$\left\langle \frac{d\phi}{dt} \right\rangle = \langle\Omega\rangle - \frac{\omega_o F}{2qa_s}\langle\sin\phi\rangle - K\langle a^2\rangle + \langle N_2(t)\rangle$$

Putting $\langle d\phi/dt\rangle = 0 = \langle N_2(t)\rangle$ and taking the probability density of amplitude and phase perturbation to be Gaussian in nature i.e.,

$$P(a_p) = \frac{1}{\sqrt{(2\pi\sigma_{a_p}^2)}}\exp\left(-\frac{a_p^2}{2\sigma_{a_p}^2}\right)$$

$$P(\beta) = \frac{1}{\sqrt{(2\pi\sigma_\beta^2)}}\exp\left(-\frac{\beta^2}{2\sigma_\beta^2}\right)$$

$$\sigma_\beta^2 = \frac{\left[\left(F\sin\phi_s + \frac{1}{a_s^2}\right)\left(\frac{F}{a_s^2}\sin\phi_s - 2K_1a_s\right) + (3a_s^2-1)^2 + \frac{F}{a_s}\cos\phi_s(3a_s^2-1)\right]\frac{(\Omega_1/\Delta\omega)a_s}{4C_1^2\,\mathrm{CNR}\,F}}{\left[F\sin\phi_s\left(\frac{F}{a_s^2}\sin\phi_s - 2K_1a_s\right) + \frac{F}{a_s}\cos\phi_s(3a_s^2-1)\right]\left[(3a_s^2-1) + \frac{F}{a_s}\cos\phi_s\right]} \tag{16}$$

$$\sigma_{a_p}^2 = \frac{\left[F\sin\phi_s + \left(\frac{F}{a_s^2}\sin\phi_s - 2K_1a_s\right) + \frac{F^2}{a_s^2} + \frac{F}{a_s}\cos\phi_s(3a_s^2-1)\right]\frac{(\Omega_1/\Delta\omega)a_s}{4C_1^2\,\mathrm{CNR}\,F}}{\left[F\sin\phi_s\left(\frac{F}{a_s^2}\sin\phi_s - 2K_1a_s\right) + \frac{F}{a_s}\cos\phi_s(3a_s^2-1)\right]\left[(3a_s^2-1) + \frac{F}{a_s}\cos\phi_s\right]} \tag{17}$$

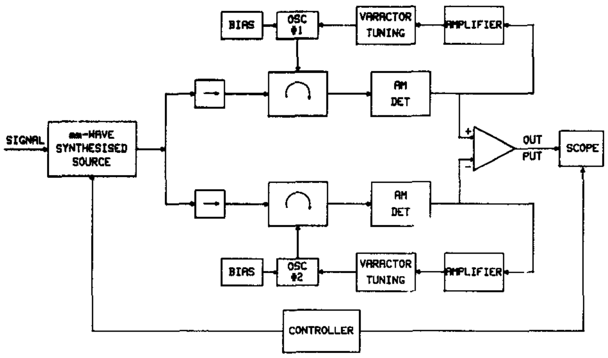


Fig. 6. Schematic of the low distortion wideband discriminator.

and also putting $\phi_s + \sigma_\beta = \pi/2$ we get the locking range expression as

$$\Omega_L = \frac{\omega_o}{2q}\frac{F}{a_s}\cos\sigma_\beta \cdot \exp(-\sigma_\beta^2/2) + K(a_s^2 + \sigma_\beta^2) \tag{17a}$$

Lock range in absence of noise and without control is

$$\Omega_{\text{won}} = \frac{\omega_o}{2q}\frac{F}{a_s} \tag{17b}$$

Then from equation (17a) and (17b) we can define locking ratio as

$$\frac{\Omega_L}{\Omega_{\text{won}}} = \cos\sigma_\beta \exp(-\sigma_\beta^2/2) + K_1\frac{a_s}{F}(a_s^2 + \sigma_\beta^2) \tag{18}$$

A plot of (18) against $(\text{CNR}\cdot C_1^2)$ is shown in Fig. 5. Varactor control of ILO gives much better performance than that of a simple ILO for lower value of CNR. But excessive control through varactor tuning is not advisable as it may push the frequency response characteristics of the oscillator into the unstable zone.

V. Low Distortion Wideband Discriminator

Output of an injection synchronized FM discriminator using a single Gunn oscillator contains harmonic distortion specially for a large index FM signal because of the limited linear zone of the response curve. A scheme has already been developed [13] for low distortion output. Here we propose a scheme with better output and wider lock range than that of an ordinary injection locked discriminator. The proposed scheme has been shown in Fig. 6. The proposed discriminator has a linear characteristic and can handle large index FM signal. The speciality of this scheme is that it can be used at very low level of synchronization with a better signal to distortion ratio. The response characteristics of the discriminators are sketched in Figs. 7 and 8.

VI. Experimental Results and Discussion

The experimental model of the proposed discriminator has been designed with a varactor tuned Gunn oscillator, a detector and an amplifier the entire arrangement for which is given in Fig. 9. The voltage tunable characteristics of the Gunn oscillator are shown in Fig. 10. The oscillograph as given in Fig. 11(a) exhibits the unlocked nature at the output of a

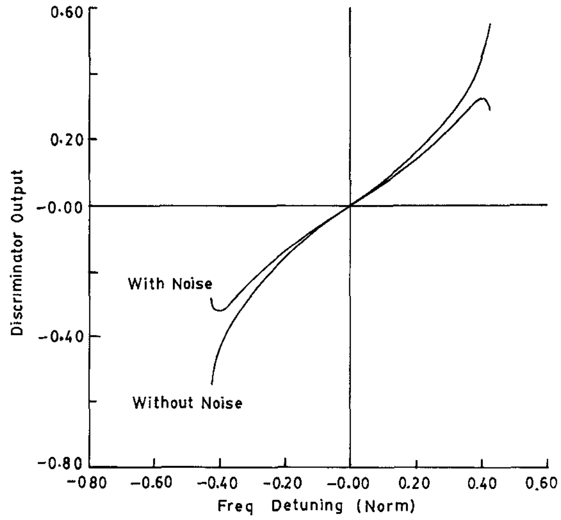


Fig. 7. Discriminator characteristics of an ordinary ILO with and without noise using two Gunn diode.

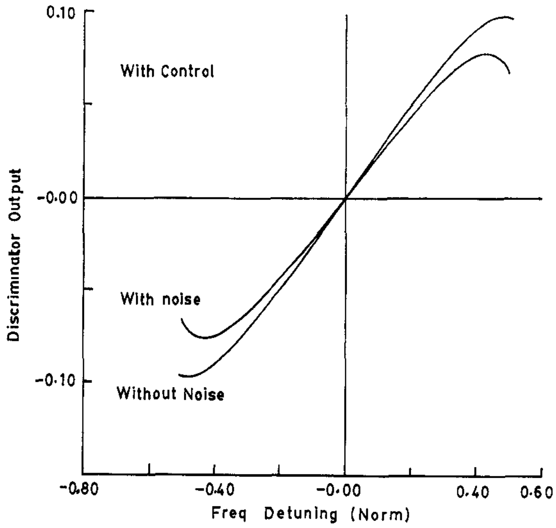


Fig. 8. Proposed discriminator characteristics in the absence and presence of noise.

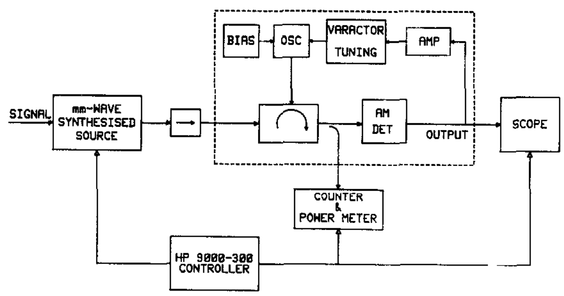


Fig. 9. Schematic of the experimental set-up.

conventional injection locked discriminator for a carrier power of 4.8 dBm when tracking an FM signal. But with the proposed discriminator a faithful detection is easily possible for a signal of the same carrier power as above and is demonstrated in Fig. 11(b). Maximum input deviation against the carrier power of the proposed system is depicted in Fig. 12 by the solid line, where as that of the conventional injection locked demodulator

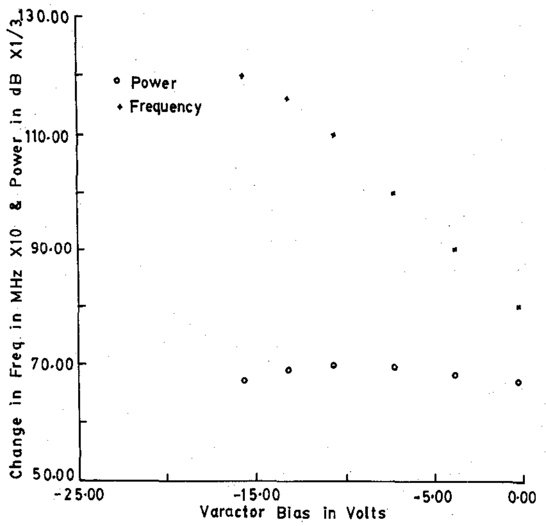


Fig. 10. Voltage tunable characteristics of the mm-wave varactor tuned Gunn oscillator.

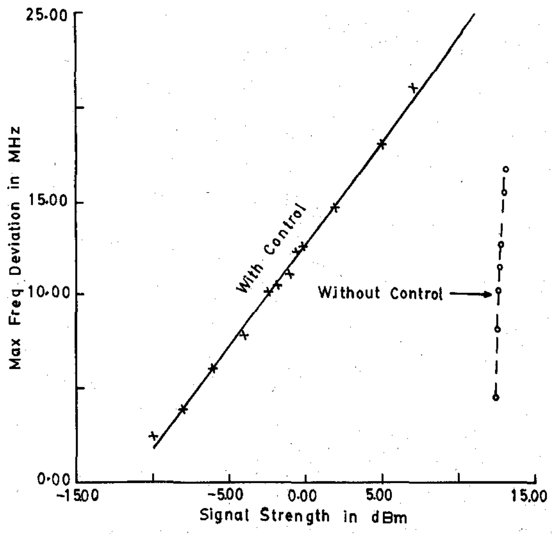


Fig. 12. Maximum input deviation handling capability against the carrier power. Solid line represents that of the VTILD and dotted one for conventional injection locked discriminator (ILD).

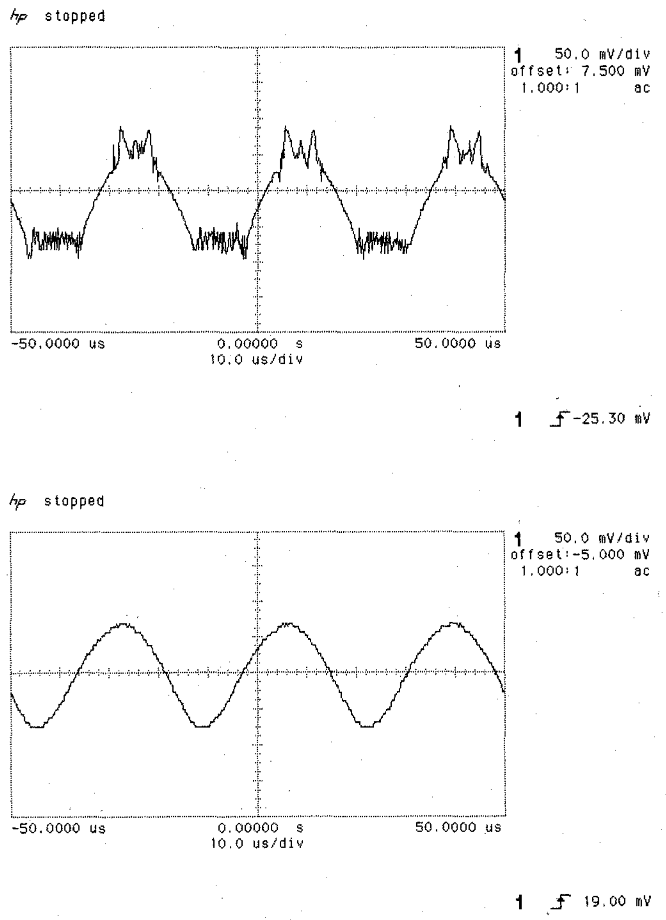


Fig. 11. Top: Oscillogram of the detected signal at the output of a conventional Injection Locked Discriminator (ILD) for a carrier power of 4.8 dBm (Free-running oscillator power = 22.4 dBm). Bottom: Oscillogram of the detected information for the same carrier power (Mod. frequency = 30 KHz) at the output of the VTILD.

is shown by the dotted curve in the same figure. It is seen from the graphs that the proposed discriminator can work faithfully with a carrier power less than 20 dB compared to that of the simple injection locked discriminator.

REFERENCES

[1] K. Kurokawa, "Injection locking of microwave solid-state oscillator," *Proc. IEEE.* vol. 61, pp. 1386–1410, Oct. 1973.

[2] C. L. Ruthroff, "Injection-locked-oscillator FM receiver analysis," Bell Syst. Tech. J., vol. 47, pp. 1653–1661, Oct. 1968.

[3] T. L. Osborne and C. H. Elmendrof, IV, "Injection-locked avalanche diode oscillator FM receiver," *Proc. IEEE (Lett.),* vol. 57, pp. 214–214, Feb. 1969.

[4] B. N. Biswas, *Phase Lock Theories and Applications.* Oxford and IBH, 1988.

[5] R. V. Khokhlov, "A method of analysis in the theory of sinusoidal self oscillation," *IRE Trans.,* vol. CT-7, p. 398, Dec. 1960.

[6] P. Z. Peebles, Jr. and A. H. Green, Jr., "A microwave discriminator with easily adjusted bandwidth," *Proc. Southeastcon,* Apr. 1–4, 1979, pp. 275–277.

[7] T. P. Chattopadhyay, "Efficient FM-AM conversion through injection-locking of an X-band Gunn oscillator," *JIETE,* vol. 32, pp. 428–434, June 1986.

[8] E. Imboldi and G. R. Slette, "AM to PM conversion and intermodulation in non-linear devices," *Proc. IEEE (Lett.),* vol. 61, p. 796, June 1978.

[9] B. N. Biswas, S. K. Ray and P. Banerjee, "Conversion of amplitude modulation to phase modulation," *Int. J. Electronics,* vol. 43, pp. 273–285, 1977.

[10] W. A. Edson, "Noise in oscillator," *Proc. IRE,* vol. 48, pp. 1454–1466, Aug. 1960.

[11] T. Saito, T. Takagi and K. Mano, "Response of a pull-in oscillator for random noise coincident with synchronising signals," *Electron Comm.,* Japan, vol. 151-A, no. 1, pp. 20–29, 1968.

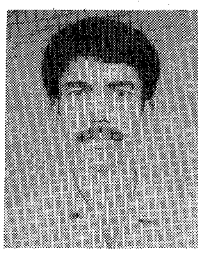
[12] P. I. Kuznetsov, R. L. Statonovitch, and V. I. Tinkonov, *Non-linear Transformations of Stochastic Processes.* New York: Pergamon, 1965.

[13] B. N. Biswas, D. Mondal, and P. Pal, "Low-distortion lock-in discriminator," *Electron. Lett.,* vol. 24, pp. 1398–1399, Oct. 1988.

B. N. Biswas (M'91) received the M.Sc. and Ph.D. degrees in 1961 and 1967, respectively, from the University of Calcutta, Calcutta, India, with a University Gold Medal at the Master's level.

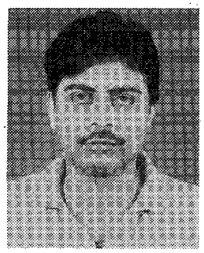
Since 1962, he has been associated with Burdwan University, Burdwan, India where he has been teaching and researching the field of electronics and communications. In 1969, he was with the University of Minnesota as a Visiting Assistant Professor. He has delivered lectures at the Czechosolak Academy of Sciences, the University of Bath, the University of Pisa, the University of Erlangen, the University of Kyoto, Okayama University and KMTL, Bangkok.

Dr. Biswas has published more than 120 research papers on nonlinear oscillations, phase-locked loops, microwave injection-locked oscillators, demodulators and optically injection-locked oscillators. He has published the book, *Phase-Lock Theories & Applications* (India: Oxford & IBH) and supervised the Ph.D. works of more than a dozen students. He received the K. S. Krishnan Memorial Award of IETE, India, and the National Lecrureship from the University Grants Commission (India) and has been elected Fellow of the West Bengal Academy of Science and Technology. He has participated in numerous national and international conferences and served on various conference program committees. He has also served as a reviewer for many national and international journals.



A. P. Sinha was born in West Bengal, India on October 24, 1966. He received the M.Sc. degree in physics with specialization in electronics from the University of Burdwan, India in 1989.

In December 1990 he joined the Physics Department, Burdwan University as a JRF and has been working towards the Ph.D. degree. His research interests includes automatic frequency control circuits in the microwave, mm-wave and optical frequency domain and fibre-optic communication techniques.



P. Lahiri was born in Calcutta, India in 1964. He received the B.Sc. degree from Calcutta University and M.Sc. degree from Kalyani University, all in physics, in 1985 and 1988, respectively.

Currently, he is working towards the Ph.D. degree in physics at Burdwan University, Burdwan, India. His research interests include nonlinear oscillations, microwave and mm-wave communication and optical microwave interaction.

D. Mondal (M'92) was born in West Bengal, India on March 16, 1963. He received the B.Sc. and M.Sc. degrees with first class in physics, both from the University of Burdwan, India in 1983 and 1985, respectively.

Since May 1987 he has been working as a JRF and afterwards as a Scientific Officer in the Physics Department, Burdwan University, under two different projects sponsored by the Department of Electronics, Govt of India. He submitted his Ph.D. thesis in September 1991. His area of research interests are microwave and mm-wave communication systems, microwave optical interaction and digital signal processing. He has published more than twenty papers in the national and international journals of repute and symposium digests.

Mr. Mondal was a participant of a course at ICTP, Trieste, Italy. He was the recipient of the National Scholarship and the URSI Young Scientist Award. He has attended many national and international symposium. In addition, he is a member of the MTT, Com, SC, AES and ED Societies of IEEE.