A Frequency Modulator with Gain for a Space Array*

E. M. RUTZ-PHILIPP†, SENIOR MEMBER, IEEE AND E. KRAMER†, MEMBER, IEEE

Summary—An active microwave frequency modulator is described which has been devised for a retrodirective space array. In this modulator one tunnel diode simultaneously functions as amplifier, frequency translator, and frequency modulator. The modulator is an image frequency converter with a local oscillator signal injected into the modulator circuit. The frequency of the image signal is modulated by varying the frequency of the local oscillator.

The image frequency is the difference between the second harmonic of the local oscillator and the signal frequency. The frequency deviation of the image frequency signal is twice the frequency deviation of the local oscillator signal.

Since the image frequency signal is the lower modulation sideband, its phase is inverted in reference to the phase of the incoming signal. The retrodirective characteristic of the modulated space antenna is realized by the phase inversion property of the modulator. Each array element is terminated with one modulator, and the local oscillator signals that are directed to the modulators must be of equal phase. No nonreciprocal device is required to separate incoming and reradiated signals in the antenna array.

In order to determine the optimum operating conditions the analysis of the image frequency converter was derived and an experimental model was tested at 2 Gc. Amplification of the image frequency signal over the incoming signal of 27 db was obtained. The local oscillator power required by one modulator is 10 μw; the dc bias power is less than 100 μw.

INTRODUCTION

A NOVEL tunnel diode frequency modulator has been devised for a modulated retrodirective array. One application of such an array is in a space telemetry or communications system. In this type system an array on a satellite would receive a microwave CW signal from a ground transmitter and then amplify, translate in frequency and modulate the signal, and finally reradiate the modulated, translated, amplified signal back to a ground receiver station. Several papers have been published recently which describe modulated retrodirective antennas[1] and communication systems[2,3] based on this approach and the authors described a varactor diode modulator for such an array in an earlier paper.[4] The present tunnel diode modulator, with its amplification and translation properties, offers improved performance and is more flexible in systems operation than the modulation methods discussed in the above references.

The space reflector array operating in the communication system has the symmetry properties of reradiating a signal in the direction from which it had arrived. To improve the signal-to-noise performance of the improved system over the one previously reported, the modulators in the space antenna should be active devices and exhibit gain, and wide-band frequency modulation should be used instead of amplitude modulation. The use of modulators with amplification G_e in a retrodirective array permits reduction of the number of array elements by $\sqrt{G_e}$ over what would be required if nonamplifying modulators were used. Translation frequency of the reradiated signal mitigates the difficult problem of separating the received signal from the transmitted signal at the ground station of the space communication system.

For a satellite system it is important to keep the power consumption of the modulators to a minimum. Inherently, a modulator with gain requires more total drive power than a passive modulator, but in many applications some increase in power consumption is a reasonable price to pay for antenna size reduction. It still will be important to keep the power consumption of the modulator to a minimum. Also, in a satellite system the amplifying modulator should not require a nonreciprocal device for operation in the array, since such a device would appreciably increase the antenna's weight.

A frequency modulator of conventional design varies the frequency of an oscillator by changing the resonant frequency of the oscillator's tuned circuit. To vary the frequency of a signal generated in an inaccessible oscillator, a frequency conversion process is required in which the converted frequency should be in the same frequency band as the unmodulated signal.

The frequency modulator with gain is shown schematically in Fig. 1. It is a tunnel diode image frequency converter with a local oscillator signal injected into the modulator circuit. In the tunnel diode modulator circuit the incoming signal at f_s and the local oscillator signal at f_{LO} are multiplied in the nonlinear element. The modulator circuit is designed to amplify the image frequency signal whose frequency is the difference between the second harmonic of the local oscillator and the signal frequency;[5,6,7] *i.e.*, $2f_{LO}-f_s$. This image frequency signal

* Received April 12, 1963.

† IBM Federal Systems Division, 10301 Westlake Drive, Bethesda, Md.

[1] E. M. Rutz and E. Kramer, "Modulated array for space communications," *NEREM Record*, vol. 4, pp. 16–17; November, 1962.

[2] C. M. Johnson and E. L. Gruenberg, "Semi-Active Communications System for Satellite Telemetry," presented at the National Symposium on Space Electronics and Telemetry, Miami Beach, Fla., October 2–4; 1962.

[3] E. L. Gruenberg and C. M. Johnson, "Quasi-passive satellite relay communications system," *Proc. Nat'l. Convention on Military Electronics*, pp. 363–370; June, 1962.

[4] E. M. Rutz and E. Kramer, "Microwave modulator requiring minimum modulation power," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-10, pp. 605–610; November, 1962.

[5] H. C. Torrey and C. A. Whitmer, "Crystal Rectifiers," McGraw Hill Book Company, Inc., New York, N. Y., p. 113; 1948.

[6] R. A. Pucel, "Theory of the Esaki diode frequency converter," *Solid-State Electron.*, vol. 3, pp. 167–207; 1961.

[7] P. L. Fleming, "Pumped tunnel diode frequency converters with idlers," *PGMTT 1963 Nat'l Symp.*, Santa Monica, Calif., pp. 129–135.

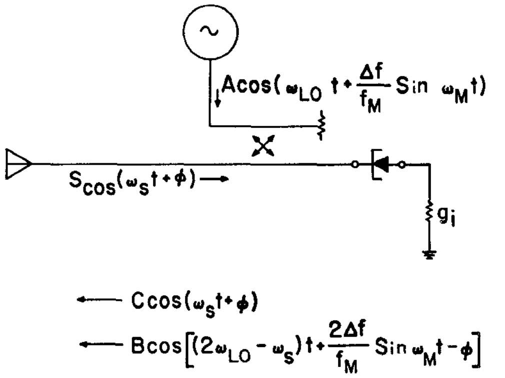

Fig. 1—Schematic of tunnel diode frequency modulator with gain.

is the lower modulation sideband; therefore its phase is inverted in reference to the phase of the incoming signal.

The image signal frequency is modulated by varying the frequency of the local oscillator. One diode functions simultaneously as amplifier, and frequency translator and modulator. The modulator is designed to operate with very low power; the required local oscillator power is 10 μw, and the dc power is less than 100 μw. No nonreciprocal device is required for its operation.

In this tunnel diode modulator, not only will the image frequency signal be amplified but the incoming signal f_s will be amplified also. Its phase will not be inverted, and it will not be modulated.

Characteristics of Space Array with Tunnel Diode Modulator

In the retrodirective array that operates with the tunnel diode image frequency converter, the phase relation requirement for retrodirective operation is obtained by the phase inversion which results when the incoming signal is converted to the lower modulation sideband. The inversion of phase in the modulators will effectively advance the phase of the reradiated wave at the image frequency at an array element where the phase of the incoming wave at the signal frequency had been delayed and vice versa. Because of the phase inversion in the modulators, the retrodirective characteristic of the array is not restricted to planar arrays. It can be obtained in curved arrays as well without requiring any phase compensation, and no phase error will be introduced over the wide angle range of operation.

In the modulated array each array element is terminated by one modulator (see Fig. 2). No interconnections between array elements are required; the transmission lines which direct the local oscillator signal to the individual modulators must, however, be of equal length. No nonreciprocal device is required to separate incoming from outgoing signals, since both signals pass through the same array element.

In the array, the difference in frequency between signal and image frequency will result in a deviation of the phase front of the reradiated image frequency signal from the wavefront of the incoming signal, as shown in

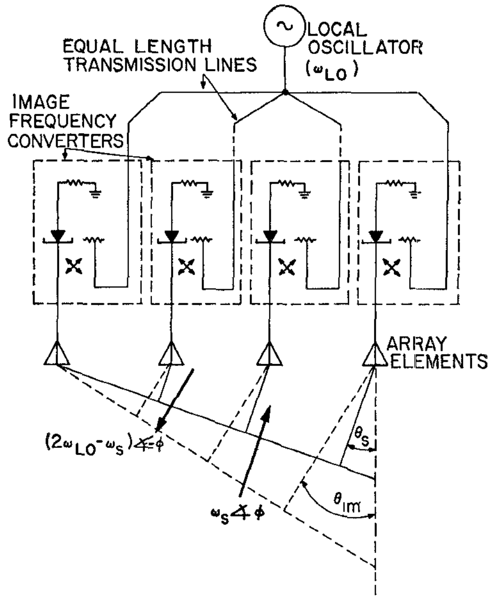

Fig. 2—Space array with image frequency converters showing redirection of incoming wavefront by means of the frequency translation of the image frequency signal ($2\omega_{LO}-\omega_s>\omega_s$).

Fig. 2. The relation between the angle of the wavefront of the incoming signal θ_s and the angle of the wavefront of the reradiated image frequency signal θ_{im} is given by

$$\frac{\sin \theta_s}{\sin \theta_{im}} = \frac{2f_{LO} - f_s}{f_s}, \qquad (1)$$

where θ_s and θ_{im} are the angles between the Poynting vector and the normal to the antenna. For a small difference in frequency between signal and image, the change in direction of the reradiated wave can be neglected.

However, there are certain system applications where reradiation in a direction which differs by a predetermined angle from the direction of the incoming wave is desirable. A space communication system operating with image frequency converters in the space antenna will be capable of directing the wave reradiated by the space antenna to different receiver stations. Since the translation frequency of the tunnel diode converter can be varied by changing either the signal frequency or the local oscillator frequency, the reradiated wave can be directed to a different receiver station by simply adjusting the frequency of the ground transmitter station. This assumes, however, either a synchronous satellite, or it requires tracking of the satellite orbit with the transmitter frequency. The capability of redirecting the reradiated wavefront is fairly independent of the attitude of the space antenna for operation not too far from broadside ($\theta \leqq 30°$) where the sine of the angle in (1) can be approximated by the angle.

In addition to the image frequency signal which is reradiated by the space array with tunnel diode modulators, the incoming signal and the local oscillator signal can also be reradiated. While the incoming signal is amplified in the modulator circuit, it will not be modulated, and therefore, will not carry information. The phase of the signal when being amplified in the modulators will not be inverted. Consequently the wave at the signal frequency will not be reradiated in the direction of the ground transmitter. For the signal frequency the space antenna functions as a mirror with gain and not as a retrodirective array.

The reradiated local oscillator signal will always form a beam broadside to the array; the local oscillator will carry information. The reradiation of the local oscillator can be suppressed simply by adding to each array element a circuit which diplexes by means of filters.

Image Frequency Converter

The performance characteristics of the space array with tunnel diode image frequency converters are derivable just from theoretical considerations. It still remains to prove that the tunnel diode converter can be operated with very low local oscillator power and very low dc bias power. In order to determine these optimum operation conditions, the analysis of the tunnel diode frequency converter is derived, and experimental confirmation is given.

The image frequency converter can be analyzed by the conventional method which assumes that the signal power is small in comparison to the local oscillator power. The three-terminal pair linear equivalent circuit which was derived by Peterson and Hussey[8] is used. While this equivalent circuit was derived for a passive circuit, it can also represent the active tunnel diode converter. Though the same equivalent circuit is used, the passive and active devices are analyzed quite differently.

The three-terminal pair network will be reduced to a network having only two pairs of terminals by connecting a fixed admittance (g_i) to the third terminal pair.

The Y matrix for the equivalent circuit for the signal-to-image frequency converter is given by

$$\begin{Vmatrix} g_0 - \dfrac{g_1^2}{g_0 + g_i} & g_2 - \dfrac{g_1^2}{g_0 + g_i} \\ g_2 - \dfrac{g_1^2}{g_0 + g_i} & g_0 - \dfrac{g_1^2}{g_0 + g_i} \end{Vmatrix}, \tag{2}$$

where g_0 is the average value of the nonlinear tunnel diode conductance, g_1 and g_2 are the fundamental and the second harmonic conversion conductances. They are the Fourier coefficients of the series which is given by

$$g(t) = g_0 + g_1 \cos \omega_{LO} t + g_2 \cos 2\omega_{LO} t + \cdots . \tag{3}$$

For the first approximation, the reactive elements in the tunnel diode equivalent circuit are not considered. This is permissible at a single frequency, where all the reactive circuit elements are tuned out.

In the modulator circuit the image frequency signal is generated by two different processes. In the first, the image frequency signal is generated by the beat between the second harmonic of the local oscillator frequency and the incoming signal. For this modulation process the transfer from the voltage at the signal frequency to the current at the image frequency is proportional to the second harmonic conversion conductance g_2. In the second, the image frequency signal is generated by an indirect path. The IF signal, which is produced by the beat between the fundamental of the local oscillator and the incoming signal, in turn produces a voltage at the image frequency in a beat between the fundamental of the local oscillator and the IF signal. For this modulation process the transfer from the voltage of the signal frequency to the current at the image frequency is proportional to the square of the fundamental conversion conductance g_1.

The e-i characteristic of a tunnel diode is not a monotonic function; the conductance parameters g_0, g_1, and g_2 will therefore vary over a large range in magnitude and can change sign depending on bias point and local oscillator power. Thus, depending on the operating points, the tunnel diode image frequency converter will function either as a passive or active device. It will be an active device when it meets one of the general activity conditions.[9] Such conditions for the image frequency converter are given by

$$g_0 - \frac{g_1^2}{g_0 + g_i} < 0$$

$$\left(g_0 - \frac{g_1^2}{g_0 + g_i}\right)^2 < \left(g_2 - \frac{g_1^2}{g_0 + g_i}\right)^2 \neq 0. \tag{4}$$

The activity conditions depend entirely on the diode's equivalent circuit parameters and the diode's parameters in reference to the third terminal pair termination. The tunnel diode image frequency converter will become an active device for different operating ranges. The requirements for activity are that either g_0 be negative or, for positive g_0, that either g_1^2 be larger than $g_0(g_0+g_i)$ or that g_2 be larger than g_0. (The activity conditions of (4) contains the assumption that, at no point the negative g_0 can become larger than the negative g_2. This assumption is always valid for the tunnel diode characteristic.)

When g_0 is negative, the incoming signal effectively becomes amplified first and then converted (when g_1 or g_2 are not zero). When g_1^2 is larger than $g_0(g_0+g_i)$, the amplified signal at the image frequency will result primarily from the conversion to the IF frequency signal by the beat between local oscillator and signal, which in turn generates the image frequency signal by beating the IF signal with the local oscillator. When g_2

[8] E. Peterson and L. W. Hussey, "Equivalent modulator circuits," *Bell Sys. Tech. J.*, vol. 18, pp. 32–48; January, 1939.

[9] E. F. Bolinder, "Survey of some properties of linear networks," IRE Trans. on Circuit Theory, vol. CT-4, pp. 70–78; September, 1957.

is larger than g_0, the image frequency signal is generated primarily by the beat between the second harmonic of the local oscillator and the incoming signal.

An examination of a typical e-i characteristic of tunnel diodes indicates that g_0 is negative when the operating point lies on the e-i characteristic between the current maximum and minimum. g_1^2 will be larger than $g_0(g_0+g_i)$ for operating points close to the current maximum and minimum on the e-i curve. Both of the foregoing activity conditions can be realized with small local oscillator powers. In order to realize the third activity condition, which requires that $g_2 > g_0$, a comparatively large amount of local oscillator power is required,[10] in which case the diode is driven into the reverse bias voltage region.[11]

In determining the best operating point for an image frequency converter for the retrodirective antenna, it is not only important to minimize the injected local oscillator power, but the dynamic range of operation has to be considered as well. It is the upper limit of the dynamic range that is of interest for the modulator, *i.e.*, the largest signal at the image frequency which can be obtained from the tunnel diode converter for constant injected local oscillator power. In the modulator circuit the upper limit of the dynamic range is determined by the effective local oscillator power. In the bias range where g_0 is positive, the effective local oscillator signal will be equal to the injected signal, but in the bias range where g_0 is negative, the injected local oscillator signal becomes amplified. The effective local oscillator signal can therefore become much higher than the injected *LO* signal. Therefore, when g_0 is negative the dynamic range of the modulator will be increased in proportion to the amplification of the local oscillator signal.

In an antenna in which a more limited dynamic range is acceptable, the tunnel diode can be operated where g_0 is positive and $g_1^2 > g_0(g_0+g_i)$.

Conversion Gain

The conversion gain at the image frequency can be shown to be:[12]

$$G_{im} = \frac{4g_a g_k}{(A+Bg_k)^2(g_a+g_{\text{in}})^2} \tag{5}$$

where

$$g_{\text{in}} = \frac{C+Dg_k}{A+Bg_k}$$

and $1/A+Bg_k$ is the voltage transfer function from the input terminals of the equivalent circuit of the modulator to the load admittance. A, B, C and D are the elements of the A matrix which can be derived from the Y matrix of (2). g_a is the input conductance at the signal frequency and g_k is the terminating conductance at the image frequency.

The conversion gain of the image frequency converter can be made arbitrarily large, and will approach infinity, as g_{in} (which is negative in the active device) approaches g_a. To keep the modulator from becoming an oscillator it is required, therefore, that g_{in} remain always smaller than the input admittance g_a. The parameters for meeting the stability conditions can be derived from (2) and (5).

The tunnel diode modulator will be stable when the three following conditions are met:

$$g_0 - \frac{g_1^2}{g_0+g_i} + g_a > 0$$

$$g_0 - \frac{g_1^2}{g_0+g_i} + g_k > 0$$

$$\left(g_0 - \frac{g_1^2}{g_0+g_i} + g_a\right)\left(g_0 - \frac{g_1^2}{g_0+g_i} + g_k\right) > \left(g_2 - \frac{g_1^2}{g_0+g_i}\right)^2. \tag{6}$$

In the tunnel diode modulator the incoming wave will be amplified as well. The amplification of the incoming wave is given by

$$G_s = \left(\frac{g_a - g_{\text{in}}}{g_a + g_{\text{in}}}\right)^2. \tag{7}$$

From (5) and (7) follows

$$G_s = \left[\frac{g_a(A+Bg_k) - (C+Dg_k)}{(A+Bg_k)(g_a+g_{\text{in}})}\right]^2. \tag{8}$$

Since the gain of the incoming wave in the modulator circuit will approach infinity, as g_{in} approaches g_a, the stability conditions of (6), which were derived for the image frequency converter, are valid for the incoming wave as well.

Frequency Modulation

In the tunnel diode converter frequency modulation of the image frequency signal is accomplished by modulating the frequency of the local oscillator signal injected into the tunnel diode circuit. (In the retrodirective array the local oscillator signal is generated in a microwave oscillator. Conventional methods can be used to frequency modulate the local oscillator signal.)

The frequency modulated local oscillator signal is given by

$$e_{LO} = A\cos\left(\omega_{LO}t + \frac{\Delta f}{f_M}\sin\omega_M t\right) \tag{9}$$

[10] B. Christensen, "Measurement of tunnel diode conductance parameters," Proc. IRE, vol. 49, p. 1581; October, 1961.
[11] Fleming, *op. cit.*, p. 131.
[12] G. L. Ragan, "Microwave Transmission Circuits," McGraw-Hill Book Company, Inc., New York, N. Y., pp. 549–550, eqs. (38) and (42); 1948.

where A is the peak amplitude, Δf is the frequency deviation and f_m is the modulating frequency. In the tunnel diode converter the incoming signal at frequency f_s and peak amplitude S, which is given by $e_s = \int \cos(\omega_s t + \phi)$, is multiplied with the local oscillator signal. The resulting frequency modulated image frequency signal is given by

$$e_{2f_{LO}} - f_s = B \cos\left[(2\omega_{LO} - \omega_s)t + \frac{2\Delta f}{f_M} \sin \omega_M t - \phi\right] \quad (10)$$

where B is the resulting peak amplitude. The frequency deviation of the frequency modulated image frequency signal is spread to twice the deviation of the local oscillator. The phase of the image frequency signal is inverted with respect to the phase of the incoming signal.

The linearity of frequency modulation is determined by the bandwidth characteristics of the modulator circuit. Though the reactances in the equivalent circuit of the tunnel diode, when deriving the conversion gain, were not considered, they must be taken into account when the FM characteristic is determined.

The modulator actually is terminated at the RF and IF terminals by resonant circuits. At the RF terminals an external shunt inductance was added to tune out the diode's capacitance. At the IF terminals the RF by-pass must be a conventional short-circuited half-wave transmission line; the other circuit elements separate RF, IF and dc voltages.

In the converter the bandwidth characteristics of the resonant circuits at the RF and IF terminals are interrelated as follows: the RF circuit must pass the incoming signal and the frequency modulated image frequency signal whose FM bandwidth is twice the FM bandwidth of the local oscillator signal. Its bandwidth must be at least $2(f_{LO} - f_s) + 2\Delta f$. Therefore, the requirement for the loaded Q of the RF circuit is given by

$$Q_{l_{RF}} = \frac{f_{LO}}{2(f_{LO} - f_s) + 2\Delta f}. \quad (11)$$

The bandwidth of the FM spectrum at the IF frequency is the same as the bandwidth of the FM spectrum of the local oscillator. In the image frequency converter, where the IF voltage is reflected at the IF termination, the bandwidth of the resonant circuit at the IF terminals must be as wide as the bandwidth of the FM spectrum. The requirement for the loaded Q of the IF resonant circuit, therefore, is given by

$$Q_{l_{IF}} = \frac{f_{LO} - f_s}{2\Delta f}. \quad (12)$$

The relation between the Q's of the RF and IF circuit can be derived from (11) and (12). It is given by

$$Q_{l_{IF}} = Q_{l_{RF}} \frac{(f_{LO} - f_s)[2(f_{LO} - f_s) + 2\Delta f]}{2 f_{LO} \Delta f}. \quad (13)$$

In the tunnel diode modulator the loaded Q of the RF circuit as a function of the circuit elements is given by

$$Q_{l_{RF}} = \frac{\omega_{LO} C_D}{g_a + g_{in_{RF}}}, \quad (14)$$

where C_D is the diode's effective capacitance, g_a is the admittance of the input line and $g_{in_{RF}}$ is the admittance which the modulator represents to the RF signals; it is given by (5). The loaded Q at the IF terminals as a function of the equivalent elements is given by

$$Q_{l_{IF}} = \frac{(\omega_{LO} - \omega_s) C_C}{g_i + g_{in_{IF}}}, \quad (15)$$

where C_C is the effective capacitance in the resonant circuit at the IF terminals, g_i is the conductance terminating the IF terminals and $g_{in_{IF}}$ is the admittance which the modulator represents to the IF signal; it is given by

$$g_{in_{IF}} = \frac{C' + A' g_a}{D' + B' g_a}, \quad (16)$$

where A', B', C', and D' are the elements of the A matrix representing the signal to IF converter. All the parameters of (14) and (15) are given by the equivalent circuit elements of the modulator and the operating point on the diode's e-i characteristic with the exception of C_C in (15). From (13) follows that for the first approximation, the ratio of $Q_{l_{IF}}$ to $Q_{l_{RF}}$ is proportional to the ratio of the IF frequency to the RF frequency. Since the $Q_{l_{IF}}$ in (15) is proportional to the IF frequency and $Q_{l_{RF}}$ in (14) is proportional to the RF frequency (while their denominators are of the same magnitude), C_C should be approximately equal to C_D. C_C, therefore, cannot exceed several pf. This can be accomplished by making the RF by-pass in the IF circuit of the converter a short circuited half-wave transmission line of comparatively low characteristic admittance.

Measured Characteristics

An experimental model of a tunnel diode modulator was tested at S-band frequencies. The experimental set-up is shown in Fig. 3. Instead of separating the incoming signal from the reflected signal and image signal with a circulator, they were separately measured by means of directional couplers and a balanced superheterodyne mixer. The signal and image frequency terminals are not separated; they are terminated by an admittance $g_a = g_k = 8 \times 10^{-3}$(1/ohm). The terminating admittance of the IF terminals $g_i = 3.7 \times 10^{-3}$(1/ohm). The frequency of the incoming signal is 2 Gc and of the image signal is 2.020 Gc.

Fig. 4 shows the gain characteristics of the image frequency converter as a function of dc bias. The injected local oscillator power was -20 dbm. The gain of the image frequency signal shows two maxima; the gain at the first maximum is 27 db, at the second maximum is

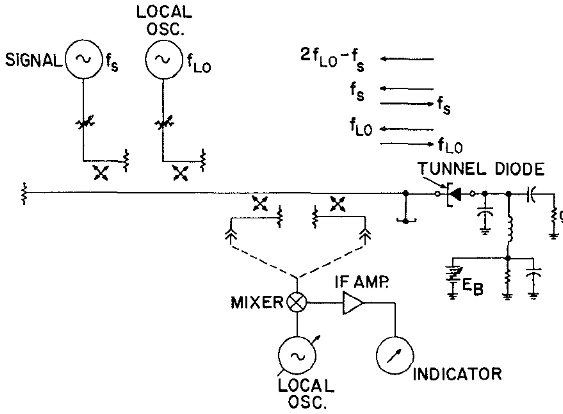

Fig. 3—Measurement setup-tunnel diode image frequency converter.

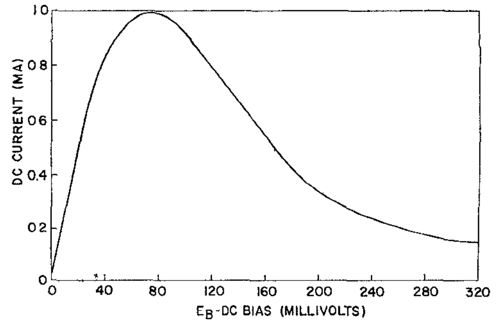

Fig. 5—*e-i* characteristics of the tunnel diode used in the image frequency converter (GE 1N3218A).

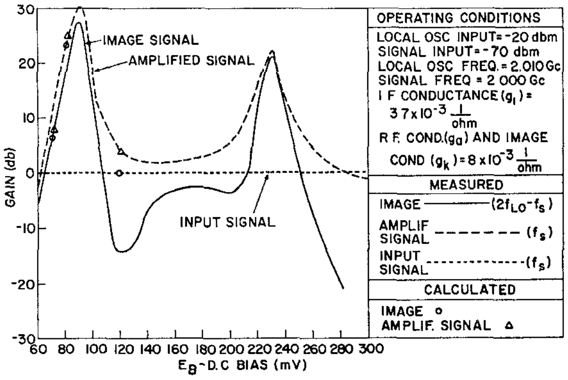

Fig. 4—Gain characteristics-tunnel diode image frequency converter.

21 db. Correlating these maxima with the e-i curve of the tunnel diode (Fig. 5) indicates that one gain maximum is close to the dc current maximum and the other is close to the dc current minimum. At these operating points $g_1^2 > g_0(g_0+g_i)$ and g_0 is positive. The dc power required to bias the tunnel diode to the current maximum is 80 μw and to the current minimum 50 μw.

The gain of the image frequency converter was calculated for several bias points for which the conductance parameters g_0, g_1, and g_2 had been derived from the e-i curve. (The calculated values are marked in Fig. 4.) There is good correlation between measured and calculated values.

Fig. 6 shows a presentation in the frequency domain taken with a spectrum analyzer of the characteristics of the image frequency converter for a fixed dc bias. Fig. 6(a) gives the incoming signal and the local oscillator signal which are directed to the modulator circuit, and Fig. 6(b) shows the amplified signals at the image frequency and at the signal frequency which had been generated in the converter.

The dynamic range of the tunnel diode image frequency converter was measured for different bias points in the bias range where g_0 is positive. The results are shown in Fig. 7. In this bias range the local oscillator signal does not become amplified and the dynamic range of the tunnel diode converter is quite limited.

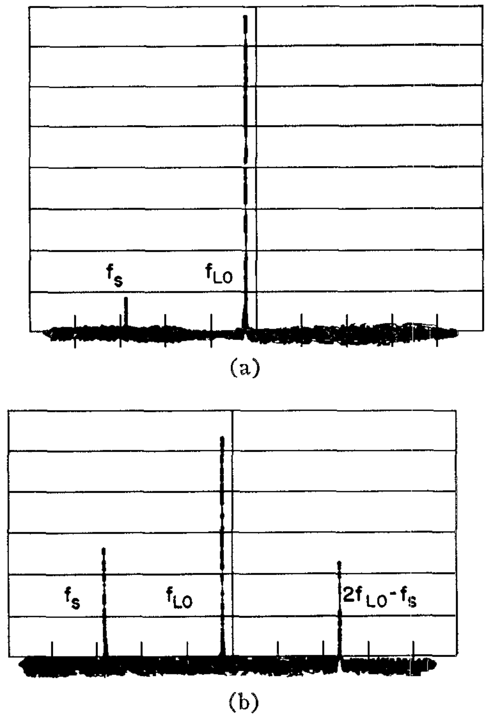

Fig. 6—RF Spectra—Tunnel diode image frequency converter.
$P_{LO} = -20$ dbm $f_{LO} = 2.010$ Gc
$P_s = -50$ dbm $f_s = 2.000$ Gc
$E_B =$ 90 mv
(a) Incoming signals.
(b) Outgoing signals.

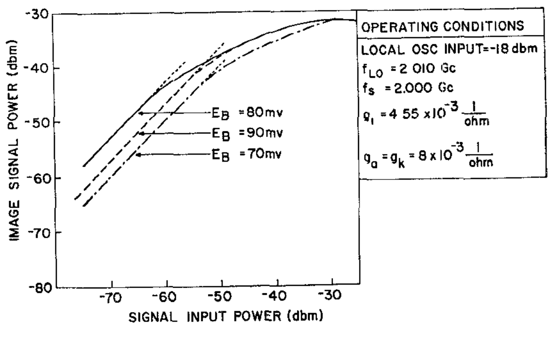

Fig. 7—Dynamic range of image signal—tunnel diode image frequency converter.

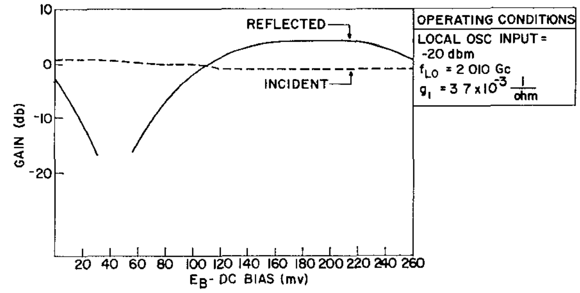

Fig. 8—Gain characteristics of local oscillator signal—tunnel diode image frequency converter.

When the injected local oscillator power is -18 dbm, the maximum power obtainable at the image frequency is -32 dbm. The dynamic range of the tunnel diode converter could be increased without increasing the injected local oscillator power by operating in a bias range where g_0 is negative. In that case, the local oscillator signal becomes amplified and the effective local oscillator of the converter is the amplified local oscillator power. Measurements were not, however, made to confirm this increase in dynamic range, since in the bias range where g_0 becomes negative the input admittance of the tunnel diode converter becomes greatly different from the admittance of the input line.

The only measurement which could be made for negative g_0 is the gain of the local oscillator signal vs dc bias. In Fig. 8 the amplified *LO* signal is compared to the incoming *LO* signal. The maximum *LO* signal gain is 6 db at 160 mv dc bias.

It is interesting to compare the characteristics of the amplified image frequency signals in Fig. 4 with the amplified local oscillator signal in Fig. 8. The amplified image frequency signal follows the small signal converter analysis where gain can be obtained when g_0 is positive, while for the large local oscillator, signal amplification can be obtained only when g_0 is negative.

Finally, in Fig. 9 the FM characteristics of the tunnel diode converter are shown. Fig. 9(a) gives the unmodulated incoming signal and the frequency modulated injected local oscillator. In Fig. 9(b) the generation and amplification of the image frequency signal and the doubling of the frequency deviation can be seen as well as the fact that the incoming signal (which also becomes amplified) is not frequency modulated.

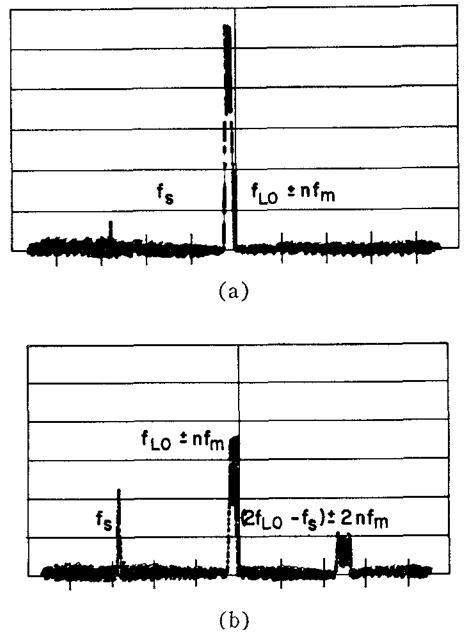

Fig. 9—RF Spectra—FM modulator with gain.
$P_{LO} = -20$ dbm $\quad f_{LO} = 2.010$ Gc
$P_s = -50$ dbm $\quad f_s = 2.000$ Gc
$\Delta f =$ 0.8 Mc $\quad f_m = 65$ kc
$E_B =$ 90 mv
(a) Incoming signals.
(b) Outgoing signals.

The full bandwidth capability of the tunnel diode frequency modulator could not be demonstrated, since the Q_l of the resonant circuit at the IF terminals in the experimental model was too high.

Acknowledgment

The assistance of E. Hurd in making the experimental measurements is gratefully acknowledged.