Conditions of Oscillation for Waveguide Mounted Tunnel Diodes

C. C. HOFFINS, STUDENT MEMBER, IEEE, AND K. ISHII, MEMBER, IEEE

Summary—**Double frequency oscillation was observed in a waveguide mounted tunnel diode circuit, due to the frequency dependency of the waveguide's distributed parameters. A general analysis of the frequency dependent diode load is made and conditions of oscillation are formulated. The analysis is extended to a 1N3219A diode mounted in a tapered RG-52/U waveguide used as an oscillator. The load impedance to the tunnel diode is derived with the diode mounted at the center of the waveguide. A numerical example involving the RG-52/U waveguide mount is presented verifying the existence of double frequency oscillation and exemplifying the oscillation conditions stated. Off center diode mounting is examined. It is concluded that the waveguide mount's distributed parameters are highly frequency dependent at the center of the guide and thus double frequency oscillation can exist when a tunnel diode is mounted at that point. With the diode mounted at any other point, only one oscillation frequency can be observed. The frequencies of oscillation of a waveguide mounted tunnel diode oscillator are determined only by the real roots of the resistive component of the total tunnel diode load impedance.**

Introduction

In several experiments involving waveguide mounted tunnel diodes in oscillator applications, it was observed that two output frequencies could be generated simultaneously using a single tunnel diode. It is, in general, not possible to generate two frequencies by coupling a single negative resistance element to one physical passive circuit. The diode can oscillate at low frequencies and it can simultaneously oscillate at microwave frequencies or, for example, it is possible to make a single tunnel diode simultaneously act as a local oscillator, amplifier and mixer.[1] In such a case, a single tunnel diode is presenting a different negative impedance at difference frequencies while nonlinearity of the diode plays an important role for mixing. In this paper, the above mentioned cases are excluded. However, an analysis of the microwave circuit employed indicates that the existence of the double frequency oscillation observed is possible for a constant negative resistance of the diode and that certain conditions of oscillation can be formulated for waveguide mounted tunnel diode circuits.

Low-frequency tunnel diode oscillators generally consist of a lumped parameter *RLC* circuit in which R, L, and C are frequency independent and thus essentially constant. However, in a waveguide, R, L, and C are distributed parameters which are frequency dependent.[2] The load impedance presented to the diode is expressed as a function of frequency, $R_L(\omega)+jX(\omega)$ where $R_L(\omega)$ and $jX(\omega)$ contain distributed parameter terms of the waveguide $R(\omega)$, $L(\omega)$, and $C(\omega)$.[3,4] This important type of frequency dependency of the input impedance parameters of a waveguide can easily be overlooked in an analysis of a tunnel diode circuit.[5–11]

A low frequency, lumped parameter *RLC* circuit coupled to a tunnel diode will oscillate at one frequency, which is readily calculated from the circuit parameters.[5,6,8] However, if a tunnel diode is coupled to a waveguide and biased to the proper value of dynamic negative resistance, it is possible for oscillation to occur at two frequencies simultaneously. Thus, in a waveguide, frequency dependent distributed parameters must be dealt with and any assumptions as to parameter constancy as encountered in a low-frequency analysis become invalid. Through consideration of frequency dependent parameters of a waveguide, the mechanism and possibility of occurrance of the double frequency oscillation encountered in a waveguide mounted tunnel diode oscillator will be examined. Experimental results will be presented as verification of the analysis. The tunnel diode will be operated at a small signal level, therefore, in this theoretical analysis, for simplicity, it is assumed that the diode is operated in the linear dynamic negative resistance region with a small signal level and therefore it is *assumed* that the nonlinear effect of negative resistance need not necessarily be considered.

Manuscript received February 28, 1963; revised August 26, 1963. This research is supported partly by a Frederick Gardner Cottorell grant to Marquette University, and partly by the University Committee on Research Grant, Marquette University.

The authors are with the Department of Electrical Engineering, Marquette University, Milwaukee, Wis.

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[4] K. Ishii and C. C. Hoffins, "Extending tunnel diode operating frequency," *Electronics*, vol. 35, pp. 42–45; June, 1962.

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[10] R. F. Trambarulo and C. A. Burrus, "Esaki diode oscillators from 3 to 40 kMc," Proc. IRE, vol. 48, pp. 1776–1777; October, 1960.

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General Frequency Dependency Analysis

The condition for oscillation of a tunnel diode is given by Dermit[5] (1)

$$Z = R_L + R_s - \frac{R}{1 + R^2\omega^2C^2} - j\frac{R^2\omega C}{1 + R^2\omega^2C^2} + j\omega L = 0 \tag{1}$$

where

Z is the total circuit impedance
R_L is the series resistance of the external circuit
R_s is the spreading resistance
R is the negative resistance (absolute value)
C is junction capacitance
L is the inductance of the external circuit and
ω is the operating angular frequency.

In a conventional low-frequency oscillator circuit, R_L and L can be considered to be frequency independent and thus essentially constant. Upon examining (1), it is seen that both the real part and the imaginary part must vanish if steady sinusoidal oscillation is to take place, that is

$$R_L + R_s - \frac{R}{1 + R^2\omega^2C^2} = 0 \tag{2}$$

and

$$\frac{R^2\omega C}{1 + R^2\omega^2C^2} - \omega L = 0. \tag{3}$$

Consider the real component of the circuit impedance given by (2). If curves of R_L+R_s and $R/(1+R^2\omega^2C^2)$ are plotted simultaneously as a function of frequency, oscillation can occur only at frequencies at which the two curves intersect, that is at frequencies at which a solution to (2) exists. In the case of an ordinary circuit containing frequency independent parameters, only one real frequency of oscillation ω_0 can exist and is given by Dermit[5]

$$\omega_0 = \frac{1}{RC}\sqrt{\frac{R}{R_L + R_s} - 1} = \sqrt{\frac{1}{LC} - \frac{1}{R^2C^2}}. \tag{4}$$

Similar conditions must hold for (3).

Generally, in a microwave circuit, R_L, R_s, L, R, and C are functions of the operating frequency.[2] Again, upon examining (1), it is seen that both the real and imaginary components of (1) must vanish for steady sinusoidal oscillation to occur. Thus

$$R_L(\omega) + R_s(\omega) - \frac{R(\omega)}{1 + R^2(\omega)\omega^2C^2(\omega)} = 0 \tag{5}$$

and

$$\frac{R^2(\omega)\omega C(\omega)}{1 + R^2(\omega)\omega^2C^2(\omega)} - \omega L(\omega) = 0. \tag{6}$$

Here also, if curves of $R_L(\omega)+R_s(\omega)$ and

$$\frac{R(\omega)}{1 + R^2(\omega)\omega^2C^2(\omega)}$$

are plotted as functions of frequency, oscillation can occur only at frequencies at which a real solution to (5) exists. However, if $R_L(\omega)+R_s(\omega)$ is plotted, the curve is no longer a straight line as in the case of the frequency independent circuit. The curve can be positioned with respect to

$$\frac{R(\omega)}{1 + R^2(\omega)\omega^2C^2(\omega)}$$

such that no real solution exists, such that one real solution exists, or such that two real solutions exist. Thus the circuit would not oscillate, oscillate at one frequency, or oscillate at two frequencies, respectively. The frequency or frequencies of oscillation are the roots of (5) and (6). Since the functions $R_L(\omega)$, $R_s(\omega)$, $C(\omega)$, and $L(\omega)$ are not explicitly known, a solution such as (4) cannot be written and such a solution generally involves the solution of a transcendental equation.

It is also required that a solution to (6) exists. Note here that a plot of $\omega L(\omega)$ as a function of frequency no longer passes through the origin as in the case of a lumped parameter circuit, but rather approaches infinity as the cutoff frequency of the waveguide is approached. Thus more than one real solution to (6) is possible when

$$\omega L(\omega) = \frac{R^2(\omega)\omega C}{1 + R^2(\omega)\omega^2C^2(\omega)}.$$

Eq. (1) need only be satisfied approximately. An exact solution to (6) indicates natural resonance. However, the frequency of oscillation is determined by (5), and if (6) is not satisfied simultaneously, a forced oscillation will occur at frequencies which are solutions to (5) but with reduced efficiency and consequently a low power output. Thus, for reasonable oscillator output, the conditions of oscillation are summarized in (7)

$$\left.\begin{aligned} R_L(\omega) + R_s(\omega) - \frac{R(\omega)}{1 + R^2(\omega)\omega^2C^2(\omega)} &= 0 \\ \text{and} \quad \frac{R^2(\omega)\omega C(\omega)}{1 + R^2(\omega)\omega^2C^2(\omega)} - \omega L(\omega) &\approx 0. \end{aligned}\right\} \tag{7}$$

These solutions must, however, lie within the waveguide's passband.

It should be noted that, in an ordinary lumped parameter circuit, oscillation will occur only at one frequency even though several solutions to the real component of (1) could exist if R_L were made frequency dependent. This is seen by examining (3). Since ωL is zero at zero frequency, a plot of ωL as a function of frequency passes through the origin and does not bend indicating one intersection with a plot of

$$\frac{R^2\omega C}{1 + R^2\omega^2 C^2}$$

at one frequency. At other frequencies, the reactive component of (1) is so high that output efficiency is very small for all practical purposes and any forced oscillation that may occur could not be detected.

Specific Case Analysis

Consider a microwave circuit consisting of a tunnel diode mounted in a waveguide operating as an oscillator. A typical configuration of such an oscillator is shown in Fig. 1.[4,12,13] This type of waveguide mount was used in the experimental work in which double frequency oscillation was observed. The mounts were originally designed to extend the operating frequency of a 1N3219A *S*-band stripline tunnel diode to *X* band.[13] The tapered waveguide is used for several purposes. First, the reduced height portion of the guide possesses a low input impedance necessary for proper matching of the waveguide "load" to the diode. Secondly, the height of the narrow portion of the guide is equal to the thickness of the diode package, thus allowing the diode contact surfaces to blend into the walls of the waveguide transforming the diode's package capacity;[14] the narrow portion of the waveguide to the standard size rectangular waveguide. Additional impedance matching is provided in one of the mounts by positioning the diode at any point along the cross section of the guide transverse to the direction of propagation. Thus the impedance presented to the diode can be varied by positioning the diode off center in the guide. This arrangement is seen more clearly in Fig. 2. The waveguide used was RG-52/U. Provisions for biasing consisting of splitting the guide[4] and using an RF by-pass disk[15] are not shown. The waveguide mounts are operated in the TE_{10} mode.

The input impedance to the waveguide mount at the diode terminals is obtained using a modification of the method of Tanaka.[3] This impedance is the ac load presented to the diode during normal operation. Consider half the mount as shown in Fig. 2. The contact surfaces of the stripline type diode used are small, and can therefore be considered as part of the waveguide wall. The actual diode can then be considered to be connected between two points on the upper and lower walls of the guide. Also, since the distance between the reduced height walls is small (approximately 1/40 wavelength) at the design frequency, the lead length of the diode is assumed to be negligible[16] and for simplicity the diode can again be assumed to be connected directly to the terminals of the microwave circuit for which the input impedance Z_i is to be computed. Z_i is obtained by connecting two sections such as shown in Fig. 2 in parallel. The input impedance to a waveguide, operated in the TE_{10} mode, at the center of the guide is given by (8).

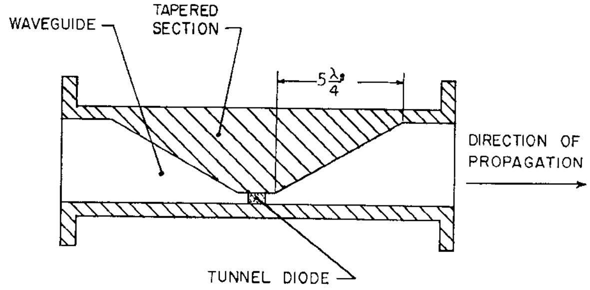

Fig. 1—Waveguide mount for stripline tunnel diode.

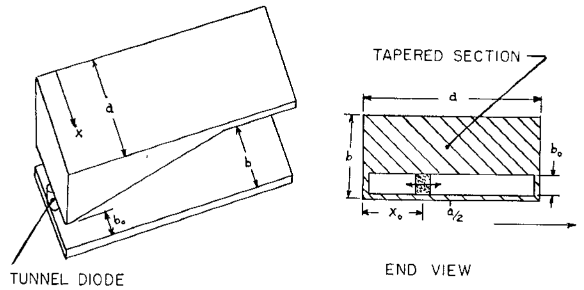

Fig. 2—Half of the tunnel diode waveguide mount showing definitions of variables used in the impedance derivation.

$$Z_k = \sqrt{\frac{\mu}{\epsilon}} \cdot \frac{1}{\sqrt{1 - (\lambda/2a)^2}} \tag{8}$$

where

μ is the permeability of free space

ϵ is the permittivity of free space

a is the width of the waveguide (0.900 ins for RG-52/U)

λ is free space wavelength ($\lambda = K/f$, K is velocity of light, f is frequency).

[12] K. Ishii and C. C. Hoffins, "X-band operation of S-band Esaki diodes," Proc. IRE, vol. 50, pp. 1698–1699; July, 1962.

[13] C. C. Hoffins and K. Ishii, "Operation of Commercial Tunnel Diodes Beyond Cutoff," presented at *N.E.C.* Technical Program, Research Preview Session, Chicago, Ill.; October 10, 1962.

[14] The diode package capacity is absorbed along with the junction capacity into distributed capacitance of the waveguide. Also, since the guide is tapered down to the diode package dimensions, the diode's contact surfaces blend into the guide walls and effectively disappear. The capacitance is not eliminated in this way, but the capacitance is transformed into a part of a distributed parameter.

[15] C. C. Hoffins and K. Ishii, "Microwave tunnel diode operation beyond cutoff frequency," Proc. IEEE, vol. 51, pp. 370–371; February, 1963.

[16] Typical microwave tunnel diode inductance (≈0.4 nanohenries) represents a 20 ohm reactance at 8000 Mc. This is *not* negligible (see Fig. 5) in a lumped parameter circuit concept. In this paper however, the lead plate or lead disk of the tunnel diode was *assumed* to be transformed into a part of a distributed parameter transmission line and became a short section of the transmission line (approximately 1/40 of a wavelength). Any microwave input impedance with or without a transmission line of 1/40 wavelength would remain unchanged except in the case where the microwave impedance is extremely low. This approximation will fail when the diode is mounted extremely close to the waveguide wall. (See Figs. 4 and 5.)

At the reduced height end of the guide

$$Z_i = \frac{b_0}{b} Z_k, \qquad X_0 = \frac{a}{2} \tag{9}$$

where b, b_0, and X_0 are given in Fig. 2.

Eqs. (8) and (9) yield the input impedance at the center of the guide only. As the walls are approached, the impedance becomes complex rather than purely resistive, so that

$$Z_i = R_g + jX_g. \tag{10}$$

The input impedance as a function of X_0 is given by (11)[3]

$$Z_i = \frac{1}{2} \frac{T^2}{1+T^2} \frac{b_0}{b} Z_k + j \frac{1}{2} \frac{T}{1+T^2} \frac{b_0}{b} Z_k, \tag{11}$$

where

$$T = \frac{2a}{\lambda_g} \tan \frac{\pi X_0}{a} \tag{12}$$

$$\lambda_g = \frac{\lambda}{\sqrt{1-(\lambda/2a)^2}}, \qquad \lambda = \frac{K}{f}. \tag{13}$$

Combining (12), (13) and (11), the input impedance can be written as

$$Z_i = \frac{Z_K}{2}\left[\frac{T^2}{1+T^2} + j\frac{T}{1+T^2}\right]\frac{b_0}{b}\frac{\lambda_g}{\lambda}. \tag{14}$$

Plots of the real component $R_L(\omega)$ as a function of X_0 and frequency, the reactive component $\omega L(\omega)$ as a function of frequency, and inductance $L(\omega)$ as a function of frequency, obtained from (14) are shown in Figs. 3, 4, 5 and 6, respectively, for RG-52/U Waveguide with $b_0/b=0.1$. Note that $R_L(\omega)$ $\omega L(\omega)$, and $L(\omega)$ vary most rapidly at the point where X_0 approaches $a/2$. Thus it is seen that the frequency dependency of the waveguide's distributed parameters is most pronounced at $X_0=a/2$. At this point, the reactive component of Z_i approaches zero. Then

$$Z_i = \frac{Z_K}{2}[1+j0]\frac{b_0}{b}\frac{\lambda_g}{\lambda}, \qquad X_0 = \frac{a}{2}, \quad T \to \infty. \tag{15}$$

Substituting (13) into (15) and replacing $\sqrt{\mu/\epsilon}$ by 377,

$$Z_i = 188.5 \frac{b_0}{b} \frac{1}{1-(K/2af)^2}. \tag{16}$$

An idealized circuit for the diode and waveguide mount can then be represented as in Fig. 7. Thus

$$R_L(\omega) = \frac{188.5 b_0}{b[1-(K/2af)^2]}. \tag{17}$$

Now, by substituting (17) for R_L in (1), and defining terms as R_1 and R_2,

$$R_1 = R_s + \frac{188.5 b_0}{b[1-(K/2af)^2]}, \tag{18}$$

$$R_2 = \frac{R}{1+4\pi^2 R^2 f^2 C^2}. \tag{19}$$

Oscillation will occur when the real component of Z_i is equal to zero, that is when $R_1 = R_2$ and the frequencies of oscillation are given by[17]

$$f_{\substack{2\\1}} = \sqrt{\beta \pm \frac{\sqrt{\beta^2 - 4\alpha\gamma}}{2\alpha}} \tag{20}$$

where

$$\alpha \equiv 4\pi^2 - R^2C^2\left(R_s + 188.5\frac{b_0}{b}\right)$$

$$\beta \equiv R - R_s\left(1 - \pi^2\frac{K^2}{a^2}R^2C^2\right) - 188.5\frac{b_0}{b}$$

$$\gamma \equiv (R - R_s)\left(\frac{K}{2a}\right)^2.$$

When the curves R_1 and R_2 intersect at one point, the circuit oscillates at one frequency, the real solution to (5) and when the curves intersect at two points, the circuit will oscillate at two frequencies, the two real solutions to (5), f_1 and f_2 provided they lie in the waveguide passband. When both roots of (20) are imaginary, no oscillation occurs.

In the experimental work performed on one of the diode mounts, two frequencies of oscillation were detected at 7.140 kMc and 8.920 kMc. Eqs. (18) and (19) were programmed on an IBM 1620 digital computer and values of R, C, and R_s were found such that (18) and (19) would intersect at the two observed frequencies. Values obtained were, within a small error, $R = 1303.5515\ \Omega$, $C = 0.0994$ pf, and $R_s = 1.4945\ \Omega$. The diode was mounted at the center of the waveguide. Curves of $R_L(\omega)+R_s$ and

$$\frac{R^2(\omega)\omega C(\omega)}{1+R^2(\omega)\omega^2C^2(\omega)}$$

as functions of frequency are shown in Fig. 8 for various diode positions using values of R, C, and R_s obtained above. The frequencies indicated by the intersections of the curves in Fig. 8 agree very well with the experimental observations. An example of the double frequency oscillations obtained with the diode mounted at the center of the guide is shown in Fig. 9, along with the tunnel diode volt-ampere characteristic. Output was detected using a Polarad RW-T R-B1 receiver. DC bias was used on the diode, indicated by the three small divisions to right of y axis on the diode characteristic shown in Fig. 9.

Consider again the effect of mounting the diode off

[17] K. Ishii and C. C. Hoffins, "Oscillation frequency of microwave tunnel diodes," Proc. IEEE, vol. 51, pp. 485–486; March, 1963.

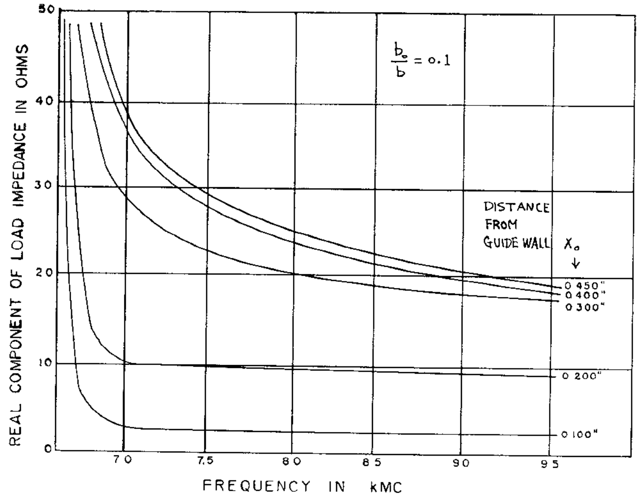

Fig. 3—Plot of the resistive component of the load impedance as a function of frequency for various diode positions.

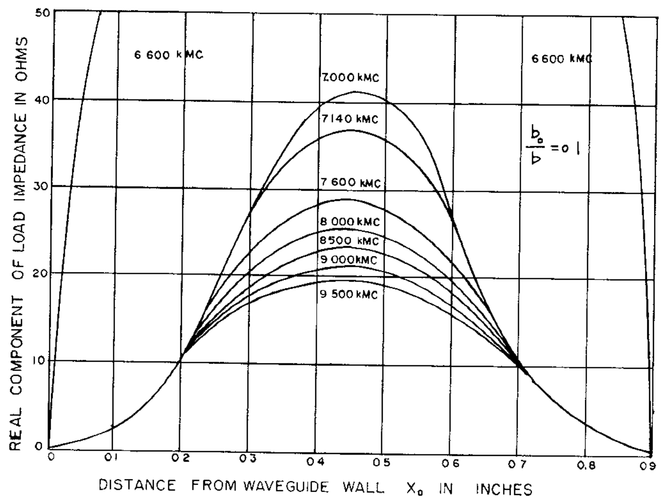

Fig. 4—Plot of the resistive component of the load impedance as a function of position for various frequencies.

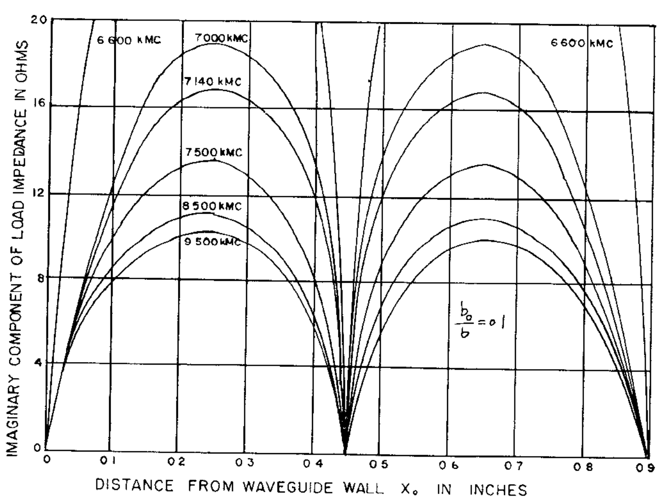

Fig. 5—Plot of the reactive component of the load impedance as a function of position for various frequencies.

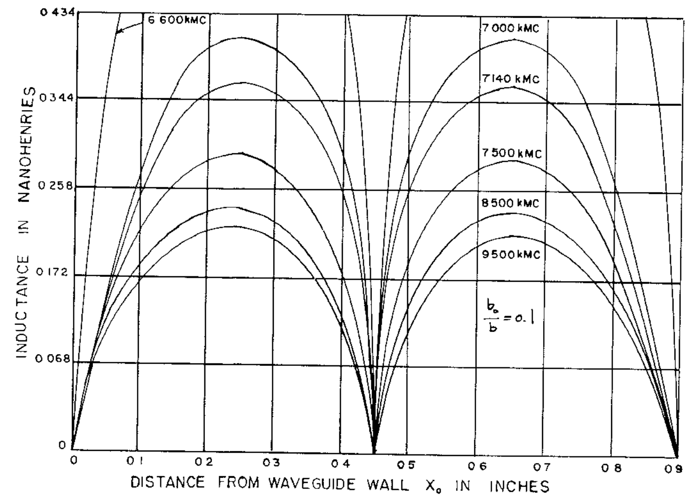

Fig. 6—Plot of the waveguide inductance as a function of position for various frequencies.

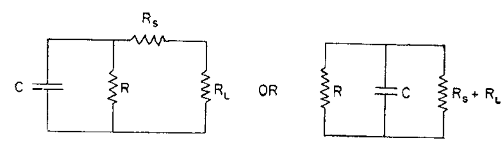

Fig. 7—Equivalent circuit for tunnel diode oscillator in which the diode is mounted at the center of a tapered waveguide.

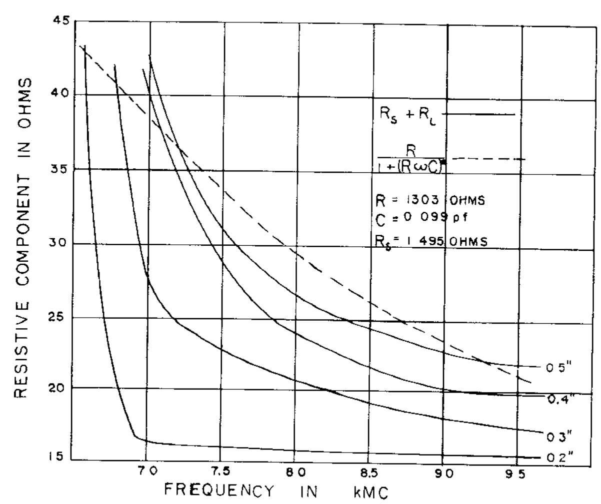

Fig. 8—Plots of the terms of the real component of the total circuit impedance for various diode positions using values of negative resistance, capacitance, and spreading resistance computed for the observed frequencies of oscillation.

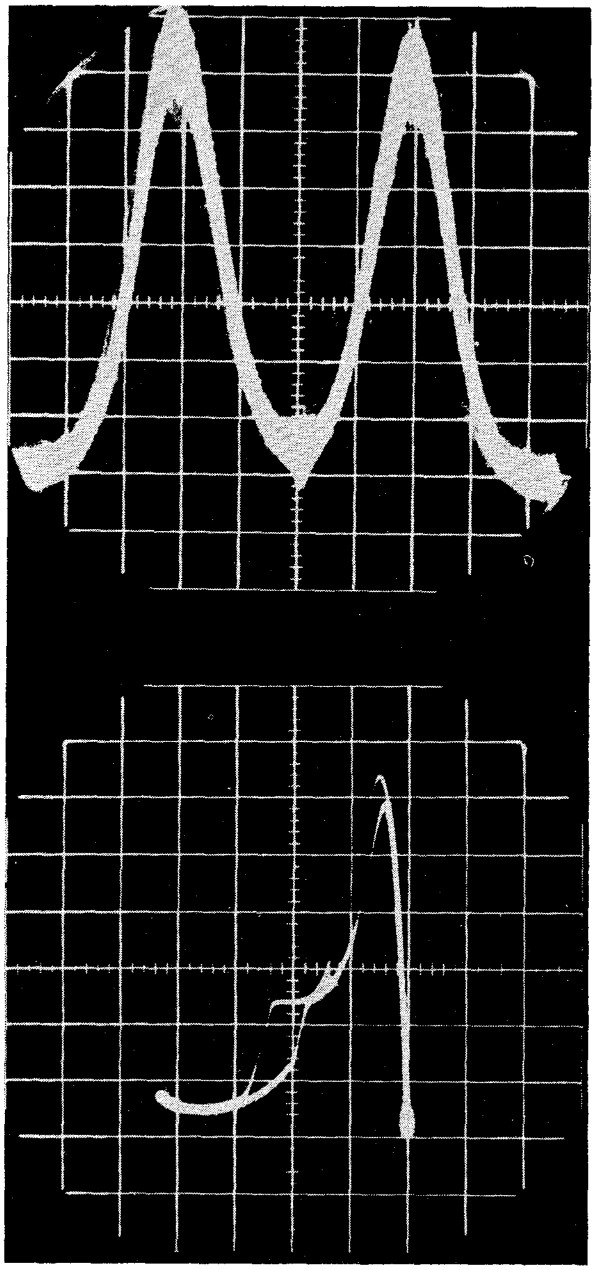

Fig. 9—An example of the double frequency oscillation obtained (top) and the corresponding diode volt-ampere characteristic (bottom) showing the dc bias point (three small divisions to right of y axis on characteristic).

center in the waveguide. Note from Fig. 4, that in RG-52/U waveguide, $R_L(\omega)$ becomes essentially frequency independent at points 0.15 inch on either side of the center of the guide. Thus, it would be expected that only one solution to (5) exists, since a plot of $R_L(\omega)+R_s(\omega)$ as a function of frequency becomes a straight horizontal line intersecting the curve at one point. $\omega L(\omega)$ remains frequency dependent near this point and has a value of approximately 14 as seen in Fig. 5. Therefore any oscillation occurring is probably a forced oscillation resulting in lower power output than would be obtained by operating the oscillator with the diode mounted at the center of the guide. Although

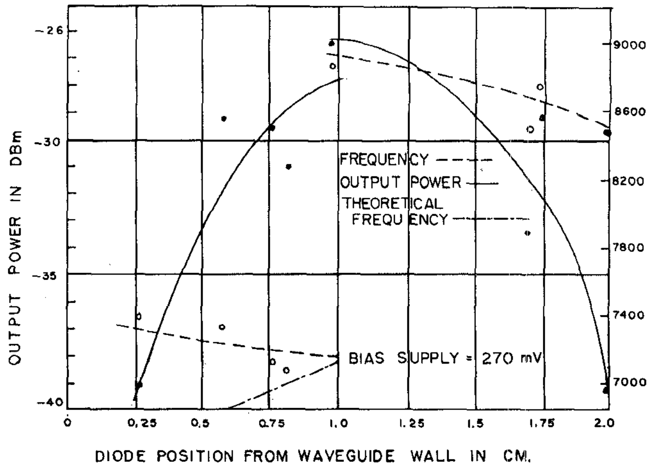

Fig. 10—Plot of frequency and output power for various diode positions.

$\omega L(\omega)$ approaches zero at the guide walls, $R_L(\omega)$ is decreasing and the power output continues to decrease due to severe impedance mismatch of the waveguide mount to the diode. The results of operating a waveguide mount[4] in which a 1N3219A tunnel diode could be mounted at any point across the guide as in Fig. 2 is shown in Fig. 10. Upon examining Fig. 10, it is seen that two frequencies can exist at the center of the guide (1 cm) while only one frequency predominates at other diode position points. Note also that output power decreases as predicted when the diode is positioned off center. From $X_0=0$ to $X_0=a/2$ the frequency increases as the diode approaches the guide center. This is in accordance with Fig. 8 as frequency increases as $R_L(\omega)$ decreases. Up to this point $R(\omega)$ and $C(\omega)$ were assumed to be constant over the small frequency range observed. However, $R(\omega)$ and $C(\omega)$ are also a function of the diode position in the guide. This position dependency of $R(\omega)$ and $C(\omega)$ in

$$\frac{R(\omega)}{1+R^2(\omega)\omega^2C^2(\omega)}$$

forms a curve such that when plotted with $R_L(\omega)+R_s(\omega)$ intersects $R_L(\omega)+R_s(\omega)$ at only one point in the region of the higher frequencies shown in Fig. 10 from $X_0=a/2$ to $X_0=a$. It is possible that the two curves intersect at a low frequency also but this frequency may be outside the passband of the waveguide or low enough that severe mismatch occurs in the circuit. For this reason, output is seen only above 8 kMc for points between $X_0=a/2$ and $X_0=a$. Since the diode was moved in the guide during the experiment, contact resistance problems appeared causing an uncontrollable change in $R_L(\omega)$. Also, some amount of series impedance was introduced into the mount due to imperfect RF bypassing of the diode's bias leads. Thus, a deviation exists between the theoretical and experimental curves shown in Fig. 10.

EXAMINATION OF EXPERIMENTAL RESULTS

The observation of two frequencies, 7140 Mc and 8920 Mc generated by the tunnel diode mount might raise a question to the effect that the tunnel diode may be oscillating at approximately 1780 Mc, and that observed outputs at 7140 Mc and 8920 Mc are the 4th and 5th harmonics, respectively, of this low frequency. In other words, the question is: are the oscillation frequencies observed merely harmonics of 1780 Mc or are they actually two separate fundamental frequencies at X band? This question was examined as follows:

1) If the observed frequency 7140 Mc is a fourth harmonic and 8920 Mc is a fifth harmonic, then the fundamental frequency must be a difference of these two frequencies (8920 Mc−7140 Mc=1780 Mc). The exact fourth harmonic is 1780 Mc×4=7120 Mc and exact fifth harmonic is 1780 Mc×5=8900 Mc. The frequency sweep range of Polarad RW-T R-B1 receiver[18] at this frequency range is 45 Mc for 7140 Mc (the signal is beating with 3rd harmonics of the local oscillator of the receiver) and 60 Mc for 8920 Mc (the signal is beating with the fourth harmonic of the local oscillator of the receiver). The output of Polarad RW-T R-B1 receiver was displayed on HP120A cathode ray oscilloscope. The frequency resolution of this system was therefore 4.5 Mc/cm for 7140 Mc and 6 Mc/cm for 8920 Mc. If the frequency observed was 7120 Mc instead of 7140 Mc, then the signal would appear 4.55 cm off the actual position observed. If the frequency observed was 8900 Mc, instead of 8920 Mc, then the signal would appear 3.33 cm off the actual position observed. The total sweep range on the cathode ray oscilloscope was 10 cm as seen in Fig. 9. Therefore, error of 4.55 cm or 3.33 cm would be easily identified. The experimental results in Fig. 9 show two separate frequencies of 7140 Mc and 8920 Mc which are beating with third and fourth harmonics of the receiver local oscillator frequency and these are not harmonically related frequencies.

2) The observed frequencies 7140 Mc and 8920 Mc were measured also by using a Microline-Model 120 cavity wavemeter. The results indicate that the frequencies obtained are not harmonically related. The frequencies obtained are close to being fourth and fifth harmonics of 1780 Mc by coincidence but are enough removed from each other that there exists no question of their being harmonics of the low frequency. The resolution of the wavemeter[19] is less than 1 Mc and absolute accuracy of the wavemeter is 1/1000. Its observed frequency difference between the detected signals and postulated harmonic frequency is 20 Mc.

3) The fact that the two frequencies obtained are fundamental frequencies can also be verified when using the Polarad RW-T receiver as a detector. The range of the receiver used is 2 to 75 kMc. If the frequencies observed were harmonics of 1780 Mc, signals would have been detected at 7120, 8900, 10680, 12460, 14240, 16020, 17800, Mc etc. up to 75 kMc. All of these signals would have appeared since they lie in the passband of the RG-52/U waveguide. It may be said that the higher frequency harmonics would be weaker than the two signals detected and thus would not be detected. However, the harmonics at 10680 Mc and 12460 Mc would not be much weaker than those at 7120 Mc and 8900 Mc. The only signals detected were those corresponding to the two observed frequencies indicating that they are fundamental frequencies. The sensitivity[18] of Polarad RW-T receiver is −85 dbm at 2 to 10 kMc, −80 dbm at 10 to 35 kMc and −70 dbm at 35–75 kMc. The signals shown in Fig. 9 are approximately 30 db above the receiver noise level at 7140 Mc and 8920 Mc.

4) The harmonic detecting ability of the RW-T receiver was tested using a 2K25 reflex klystron oscillator and 2N965 transister oscillator. The RW-T receiver could detect harmonics of the 2K25 reflex klystron oscillator, which was operated at 8.54 kMc, from the fundamental through 18th harmonic. The 18th harmonic was 154 kMc and the power output was almost noise level of the receiver but it was still detectable. The signal at 154 kMc is beyond the official range of the RW-T receiver, but, since the broad band receiver is utilizing a harmonic of the local oscillator, by careful observation, it was not difficult to identify each harmonic up to the eighteenth.

A transistor, 2N965, was operated as a relaxation oscillator in the avalanche mode. The fundamental frequency of the oscillator was 37.5 Mc. Using the RW-T receiver harmonics up to 12.02 kMc, which was 321st harmonic was still 40 db above the noise level of the receiver. Harmonics higher than 321st were not identified because of overlapping of many harmonics.

The experimental evidence indicated above suggested that, if the tunnel diode, 1N3219A, was really oscillating at 1780 Mc and its harmonics were actually generated, harmonics other than 7120 Mc and 8900 Mc could have been detected. But the experimental fact is that only 7120 Mc and 8900 Mc was observed. Signal at 1780 Mc was not detected nor were other harmonics detected. The signals detected were at only two frequencies, which were 7140 Mc and 8920 Mc.

5) The frequencies observed at X band are the only frequencies generated. This was verified in the split waveguide mount whose RF bypass radiated excessively. The signals radiated from the bypass were detected using the Polard RW-T receiver. The frequency which would be the second harmonic of 1780 Mc (*i.e.*, 3560 Mc) was *not* detected while the two X-band signals

[18] "Preliminary Instruction Manual Broadband Microwave Receiver, Model RW-T," Polard Electronics Corp., Long Island City, N. Y; 1961.

[19] "Operating Instrumentations and Technical Data, Microline Coaxial Frequency Meter Model 126 Serial 980," Sperry Microwave Electronics Co., Clearwater, Fla., Rept. No. SJ-60-00014; 1959.

were detected. These were picked up by a coaxial dipole probe.

6) Since the second harmonic of 1780 Mc, the 3560 Mc, would be present if the oscillation were taking place at 1780 Mc, the 3560 Mc S-band signal could be detected when passed through an S-band mixer fitted with a 1N23 crystal detector. The scheme used is as follows. A thin coaxial cable terminated in a pickup loop was inserted into the microwave tunnel diode mount waveguide close to the tunnel diode. The loop was close enough to be able to pick up 3560 Mc. This coaxial cable was fed into a tunable S-band cavity, which was fitted with a 1N23 crystal diode, and used as a mixer with the Polarad receiver. No S-band signal could be detected.

7) Oscillations below 500 Mc were checked with an HP417A VHF detecter and no signals were observed.

8) It should be noted that the double frequencies were observed only when the tunnel diode was mounted near the center of the waveguide. If the tunnel diode was mounted off center, only a single frequency was observed as shown in Fig. 10. If the double frequencies observed were harmonics of 1780 Mc, then why did they appear only when the diode was mounted at the center of the waveguide? If the observed two frequencies were harmonics of a lower frequency oscillation, there should be no relation to the mounting position of the diode. In other words, no matter where the diode was mounted, off center or at the center of the waveguide, the double frequency should appear at all times. But the experimental fact was, as shown in Fig. 10, the double frequencies were observed only when the tunnel diode was mounted close to the center of the waveguide. It should be noted that the reason for this double frequency oscillation was explained theoretically in a previous section and that the theory predicts that the two frequencies are generally not harmonically related.

9) Careful inspection of Fig. 9 indicates that there is a visible low-frequency beat between the two peaks. If the two peaks are harmonics of 1780 Mc, it is not possible to produce a visible low frequency beat between them.

For the above stated reasons and experimental evidence, it was concluded that the double frequencies observed were two separate frequencies and they are not harmonically related.

Conclusions

The design of a microwave tunnel diode oscillator with the tunnel diode mounted in a waveguide must take into account the frequency dependency of the waveguide distributed RLC parameters. It is due to this frequency dependent nature of the waveguide parameters, that two frequencies could be generated simultaneously using a single tunnel diode biased at one point on its volt ampere characteristic. Frequency dependent parameters are generally not found in low frequency, lumped parameter circuits, and thus, frequency dependent parameters are easily overlooked in the analysis of a microwave circuit.

The conditions of oscillation of a waveguide mounted tunnel diode circuit are that the real component of the total circuit impedance vanishes. In general, it is desirable that the imaginary component also vanishes. This corresponds to natural resonance and results in high output efficiency. However, it is not necessary for the imaginary component to vanish entirely. If reactance exists in the total circuit impedance, a forced oscillation will occur at a reduced output efficiency, and thus, the frequencies of oscillation of a waveguide mounted tunnel diode oscillator are determined only by the real roots of the real or resistive component of the total circuit impedance. It is, however, necessary that these real roots lie within the passband of the particular waveguide used.

Acknowledgment

The authors thank J. E. Billo, J. A. Stefancin, and S. Krupnik, Jr. for their assistance. The authors also thank the Marquette University Computing Center for the use of the IBM 1620 digital computer and J. H. Van Nuland for assistance in writing the program involved in the preparation of this paper.