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Integrated Tunable Cavity Gunn Oscillator for 60-GHz Operation in Image Line Waveguide

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Abstract —**The design, construction, and experimental test results of a mechanically tunable Gunn oscillator using a recessed diode metal coaxial cavity coupled to an image line waveguide is described. The oscillator frequency was changed by about 10-percent by varying the bias post length into the coaxial structure. The oscillator is designed so that both the Gunn diode and resonant cavity can be quickly replaced to provide extended frequency coverage and efficiency. This Gunn diode oscillator has provided up to 15-mW CW power at 60 GHz with 10-percent tuning range.**

I. Introduction

METAL WAVEGUIDE cavity oscillators are available now at 60 GHz. However, there is an increasing requirement for sources for image line millimeter-wave integrated circuits. Up to the present time, very little work has been reported on oscillators compatible with image line technology. A recent development of the Gunn oscillator using quartz image line was reported by Y. W. Chang [1]. In the following, a development is reported which shows how an oscillator can be integrated into image line subsystems with useable power output and good mechanical tuneability.

The millimeter-wave oscillator is designed around a recessed coaxial air-filled metal cavity which is coupled to a dielectric image line. The physical design incorporates a replacable oscillator coaxial cavity and a structure with a replaceable Gunn diode, as shown in Fig. 1.

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II. Oscillator Physical Design

The circuit as shown in Fig. 1 consists of a brass body 1.5 in long by 0.75 in wide and 0.5 in thick. The Gunn diode is threaded into a smooth brass cylinder which is inserted in the bottom of the brass body to form a resonant cavity. A brass post (0.025-in diameter) is threaded through the tuning top disk mounted on the top of the image line and through a 0.050-in-diameter hole in the dielectric. This provides a means of coupling up from the metal cavity into the image line waveguide. The dc bias voltage is applied to the top tuning disk through the tuning rod to the Gunn diode as shown in Fig. 2. Through the use of this tuning arrangement, the cavity height is variable (as tested) from 0.015 to 0.100 in over which a wide tuning range can be realized. The oscillator resonant (metal) cavity is shown in Fig. 2. The output is coupled through a narrowed opening at the top of a metal cavity into a hole of 0.050-in diameter in the alumina material which forms the image guide structure. A metal disk (0.120-in diameter) cemented to the top of the dielectric (alumina) serves as a bias connection, tuning screw mounted for the bias post, and prevents extraneous radiation from the dielectric by providing a top wall for the metal cavity. The alumina guide is 0.120 in wide, 0.040 in thick, and 1.0 in long. The wave is coupled ideally into the alumina guide in the form of the $E_{11}y$ mode. The alumina end is tapered for impedance matching into a metal waveguide structure for test and evaluation.

Although not shown on Fig. 1, a 100-pF chip capacitor was mounted between the top tuning disk and ground.

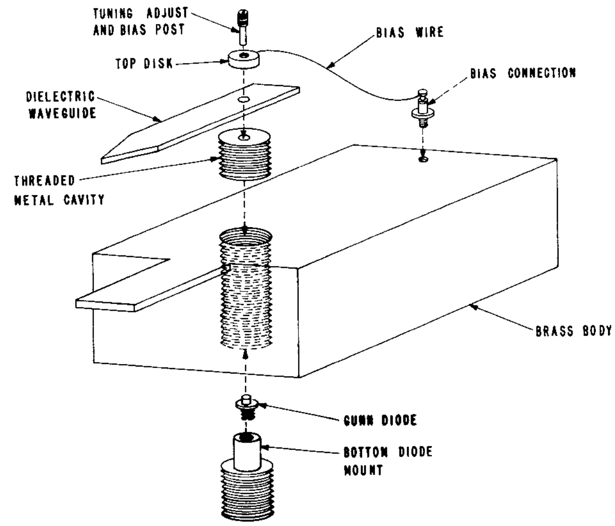

Fig. 1. Gunn oscillator, expanded view.

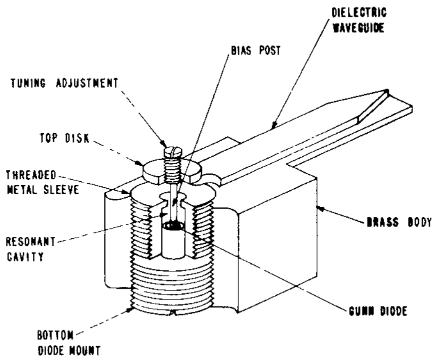

Fig. 2. Gunn oscillator, internal view of cavity.

Also, a 10-μF capacitor was placed from the bias terminal post to ground [2]. These capacitors are necessary to assure that low-frequency oscillations of large amplitudes do not destroy the Gunn diode. The bias is applied to the top tuning disk via a thin copper wire which also serves as an RF choke.

III. Equivalent Circuits

The equivalent circuit for the Gunn oscillator [3], [4] is shown in Fig. 3, where $-R$ is the negative resistance of the Gunn diode, C_j is the junction capacitance, L_p is the package inductance, C_p is the package capacitance, and R_L is the transformed load resistance. In an analysis shown in Appendix A, the values of some of these parameters are discussed.

The values of L_p and C_p are inherent in the construction of the device since the lead inductance from the top of the semiconductor surface to the top of the standoff package is always present. C_p is also largely dependent on packaging. The criterion for oscillation [3] is

$$|\mathrm{Re}\, Z_g| \geqslant |\mathrm{Re}\, Z_T|. \tag{1}$$

The $|\mathrm{Re}\, Z_g|$ is generally less than 8 Ω, so that R_L has to be fairly large for the $|\mathrm{Re}\, Z_T|$ to be small enough for

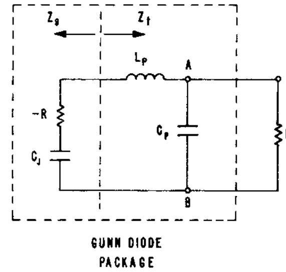

Fig. 3. Gunn oscillator, equivalent circuit.

oscillation to occur. Also for oscillation

$$\mathrm{Im}\, Z_g = -\mathrm{Im}\, Z_T. \tag{2}$$

If one can determine the operating frequency experimentally and has known values of R_L, L_p, and C_p, using (2), the value of C_j can be verified by

$$C_j = \frac{1 + \omega^2 R_L^2 C_p^2}{\omega^2 \left(L_p - R_L^2 C_p + \omega^2 C_p^2 R_L^2 L_p \right)}. \tag{3}$$

If the load across terminals AB is complex, the characteristics are changed in two ways. First, the frequency is pulled away from the nonreactive loaded condition to a new frequency where (2) applies. Second, the power output can change since the $\mathrm{Re}\, Z_T$ will be altered.

IV. Experimental Design and Performance

In the design of image line oscillators, there are inherent difficulties. In one approach [5], the diode is imbedded in a hole in the dielectric and fastened to a metal base common to both the diode and the dielectric waveguide (Fig. 4). The oscillator configuration, as shown, does not have any means of tuning; hence, neither power nor frequency could be changed except through external load impedance matching. In most cases, external matching is bulky and unpredictable, and thus is undesirable.

In the device described in this report, the cavity height is accurately controlled to assure a predictable and close control of both power and frequency. The resonant cavity which is imbedded in a metal walled cylinder with the diode located at the bottom (Fig. 2) provides a high-Q cavity for enhancement of the oscillator power. The physical means of the cavity height adjustment is shown in Fig. 2, where the length of the bias post is changed while simultaneously varying the diode and floor of the cavity relative to the fixed upper part of the cavity where the power exists. The variable cavity height provides a wide frequency tuning range.

In order to discuss the electrical performance of the oscillator, Fig. 5 is shown. This contains the detailed dimensions of the structure. The dc bias voltage is applied through the center post which is supported by a metal disk on the top of the image line guide, which also serves as a resonant transformer. This design allows change of cavity dimensions. For example, the cavity diameter a was 0.167 in, 0.190 in or, 0.250 in. The cavity height d could be varied over a continuous range from 0.011 to 0.100 in. The power

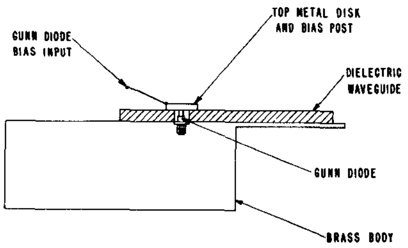

Fig. 4. An earlier oscillator design, cross section.

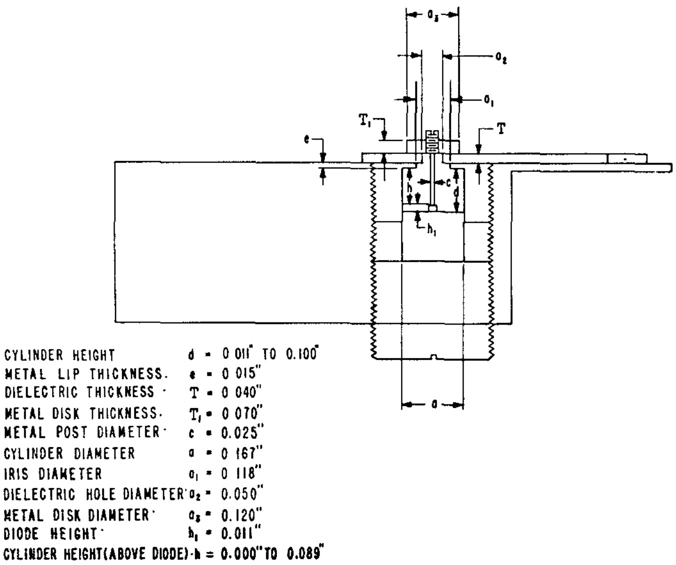

Fig. 5. Gunn oscillator assembly, side view, showing dimensions.

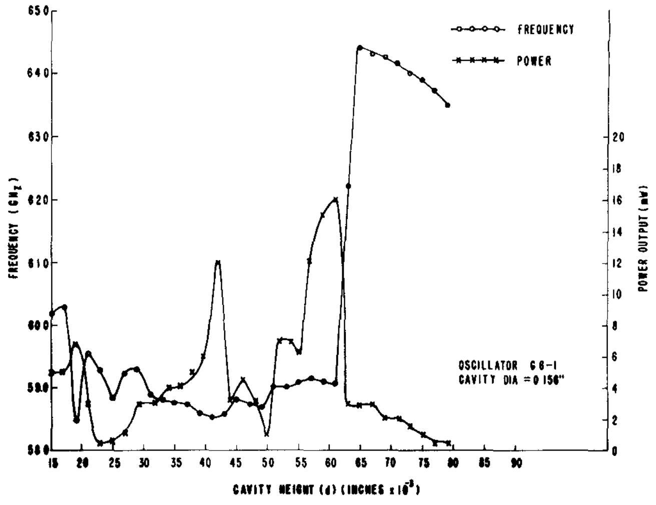

Fig. 6. Gunn oscillator G6-1 using 0.156-in cavity and 0.040-in Alumina waveguide, power and frequency versus cavity height.

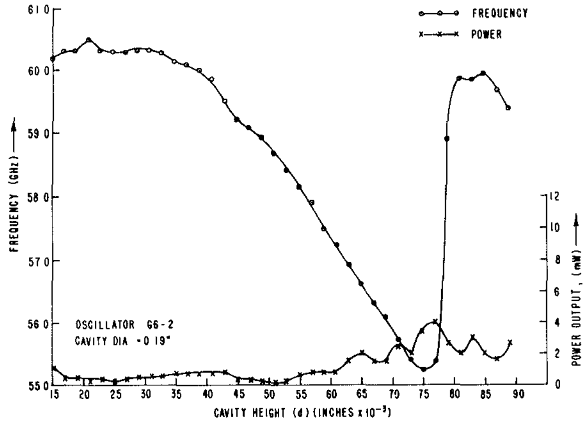

Fig. 7. Gunn oscillator G6-2 using 0.190-in cavity and 0.040-in Alumina waveguide, power and frequency versus cavity height.

generated in the cylindrical metal cavity exits through an iris to an air-filled dielectric hole covered by the metal disk. The power flows out through a 0.040-in-thick and 0.120-in-wide Al_2O_3 image guide to a metal waveguide structure for test purposes. The dielectric is tapered to better match the line when inserted into metal waveguide.

V. Data

In Figs. 6, 7, 8, and 9, the data showing frequency and power as a function cavity height d are plotted for three different cavity diameters. All data was taken using an InP Gunn diode operated near -7.8 V and 420 mA. The vendor (Varian Associates, Inc.) reported that in a metal walled cavity at 54.3 GHz, approximately 68-mW maximum rated power was obtained. Our best data indicates at 59.08 GHz a power output of 16 mW in the 0.156-in-diameter cavity.

In examining these figures, the following conclusions appear. The highest power was obtained from the smallest diameter (0.156 in) cavity. In all three sizes, the highest power peaks occurred in the range of 0.060 to 0.083-in cavity height. For any of the structures and with a given diode, the capability of being able to mechanically tune is essential to obtain useable power levels. In these structures, tuning is relatively simple and operation stable. This was not possible in previously reported image line or microstrip oscillators [1], [3]–[5], since tuning was not built into these configurations. Also, the cavity with 0.190-in diameter showed a nearly linear change in frequency with change in cavity height over a relatively broad range of tuning distance (almost 10-percent change in frequency).

A summary of the data is shown in Table I. Reference is made to the first three rows. Two power peaks were observed. The first power peak occurs at a cavity height d of about 0.040 to 0.050 in, which coincidentally appears to be about $\frac{1}{4}\lambda$ from the base of the coaxial cylinder to the iris, distanced for exit power. The distance from the coaxial cylinder base to the bottom of the reflecting tuning disk is about $\frac{1}{2}\lambda$. To show that the length of the coaxial line is nearly $\frac{1}{2}\lambda$ at the resonant frequency, we add the following (as shown in Fig. 5 and outlined in Appendix B):

$$d+e+T=\tfrac{1}{2}\lambda. \qquad (4)$$

The center rod (bias post) is surrounded by air from the coaxial cylinder base to the bottom reflecting surface of the tuning disk. By (4), for oscillator G6-1, one obtains a total cavity height of

$$1.07\ \text{mm}+0.375\ \text{mm}+1.00\ \text{mm}=2.445\ \text{mm}.$$

For 58.55 GHz, the $\frac{1}{2}\lambda$ for the TEM mode is 2.56 mm, which gives good agreement. The remaining five oscillators

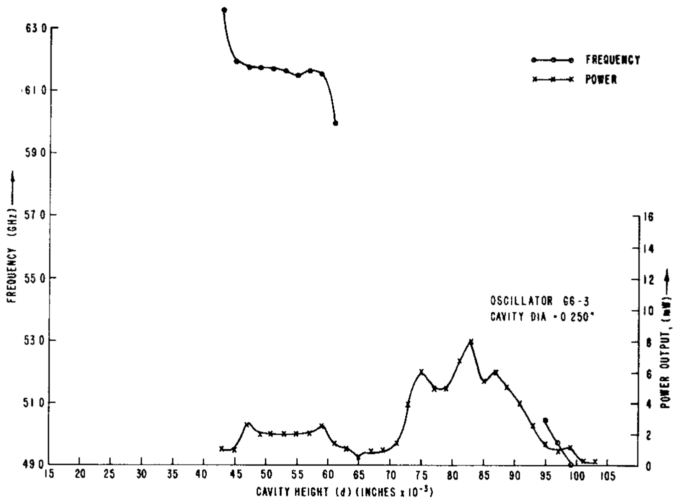

Fig. 8. Gunn oscillator G6-3 using 0.250-in cavity and 0.040-in Alumina waveguide, power and frequency versus cavity height.

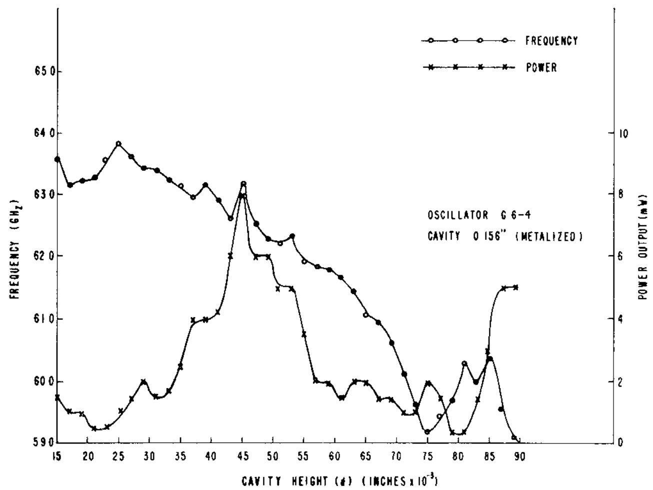

Fig. 9. Gunn oscillator G6-4 using 0.156-in cavity and 0.040-in metallized quartz waveguide, power and frequency versus cavity height.

tested also had first power peaks at frequencies where (4) is in good agreement. For second power peak, (4) does not hold for the larger cavity height d. The second power peaks occur at progressively lower frequencies as cavity diameter a is increased from 0.156 to 0.250 in. The oscillator, using three different cavities designated as G6-1, G6-2, and G6-3 used the same Gunn diode (power specifications indicated above). In the test of structure G6-4, the same cavity diameter (0.156 in) was used as G6-1, but instead of using Al_2O_3, a metallized CrAu quartz dielectric was used to form an external metal cavity around the dielectric. This metallized quartz cavity is the type reported by Chang [1]. The uncoated front side provided coupling into the quartz image line. Two things are different from the other configurations, namely, quartz is used instead of Al_2O_3, and metallization of the upper quartz surface is used as the transformer rather than the disk. Two power peaks were still obtained. The first was at $d = 0.045$ in, which is similar to the previous three cases.

TABLE I
GUNN OSCILLATOR, FREQUENCY AND POWER PEAKS VERSUS CAVITY HEIGHT

PHYSICAL CHARACTERISTICS			FIRST PEAK IN OUTPUT POWER			SECOND PEAK IN OUTPUT POWER		
OSCILLATOR STRUCTURE	THICKNESS T DIELECTRIC WAVEGUIDE mm (in)	CAVITY DIAMETER a mm (in)	CAVITY HEIGHT d mm (in)	FREQUENCY (GHz)	POWER OUTPUT mW	CAVITY HEIGHT d mm (in)	FREQUENCY (GHz)	POWER OUTPUT mW
G6-1	ALUMINA 1 02 (0 0416)	3 96 (0 156)	1 07 (0 042)	58 55	12 00	1 55 (0 061)	59 00	16 00
G6-2	ALUMINA 1 02 (0 0416)	4 83 (0 190)	1 09 (0 043)	59 50	0 80	1 96 (0 077)	55 36	4 00
G6-3	ALUMINA 1 02 (0 0416)	6 35 (0 250)	1 35 (0 053)	61 70	2 50	2 11 (0 083)	57 00	8 00
G6-4	METALLIZED QUARTZ 1 02 (0 0416)	3 96 (0 156)	1 14 (0 045)	63 0	8 30	2.24 (0 088)	60.00	5.00
G5-5	ALUMINA 1 02 (0 0416)	6 35 (0 250)	1 17 (0 046)	55 4	2 00	1.73 (0 068)	57.80	3 00
G4-5	ALUMINA 0 5 (0 0197)	6 35 (0 250)	1 04 (0 041)	52 2	5 00	1 57 (0.0618)	50 5	4 60

The second peak occurred at 0.088 in. In this case, unlike the previous three tests, a higher power (8.3 mW) was obtained at the smaller cavity height as compared to 5 mW at the larger cavity height. This test was done with a second InP Gunn diode but with similar characteristics to the first diode. Results indicate that tuning is facilitated by changes in the coaxial cylinder height. The fifth and sixth rows in Table I refer to data obtained with a third Gunn diode with similar electrical characteristics to the previous diodes mentioned, although plots of power and frequency versus cavity height are not provided. The diameter of the coaxial cavity was again 0.250 in so oscillator configurations G5-5 andG4-5 can be compared with G6-3. We note that the first power peak occurs at nearly $\frac{1}{2}\lambda$ as in the first three cases. Also, note structures G5-5 used a dielectric runner of 1.02-mm thickness and G4-5 used a runner of 0.5-mm thickness. The output powers are in the same order of magnitude. The primary source of energy is in the metal coaxial cavity.

Measurements were also made of the external Q of oscillator G6-1. The test setup for these measurements using injection locking is shown in Fig. 10. Results of these tests using oscillator G6-1 with the smallest diameter cavity (0.156 in), are shown in Table II. Q_{ext} was found to depend on the depth of insertion of the dielectric into the metal waveguide (i.e., coupling from the dielectric waveguide to the rectangular metal guide). For these measurements, the dielectric insertion was adjusted so that maximum power transfer was obtained for a given bias voltage of -7.7 V. Successive measurements were made using injection power (P_i) and oscillator power (P_{osc}) levels as shown in Table II. The range of Q_{ext} varied from 352 to 646.

The equations [6] used in the calculations for Q_{ext} are as follows:

$$Q_{ext} = \frac{2f_0}{\Delta f}\sqrt{\frac{P_i}{P_o}} \tag{5}$$

where f_0 is the center frequency, Δf is the full locking bandwidth, P_i is the input power, and P_o is the oscillator power.

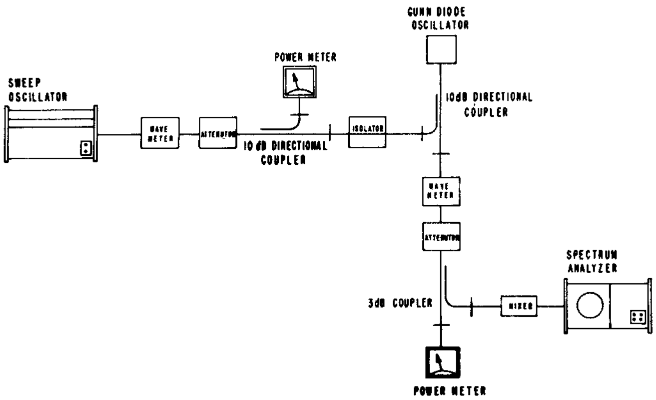

Fig. 10. Test setup for circuit Q measurement.

TABLE II
GUNN OSCILLATOR, G6-1, EXTERNAL CIRCUIT Q

P_t (mW)	P_{osc} (mW)	f_{osc} (GHz)	Δf (GHz)	Bias (Volts)	Q_{ext}
2.00	6.00	57.95	0.19	7.9	352
1.80	6.00	57.95	0.14	7.9	453
1.80	5.25	58.00	0.17	7.9	400
1.75	6.07	57.93	0.13	7.9	479
1.50	5.93	57.80	0.09	7.9	646

VI. CONCLUSIONS

An oscillator has been developed for image line configuration; the Gunn diode can be mechanically adjusted in position to change coaxial cavity height, for optimum power. Furthermore, in case of Gunn diode burnout, the Gunn diode can easily be removed and a new diode inserted.

The principle involved is to recess the diode in a coaxial cavity under the dielectric used for image line. This provides a high circuit Q around the diode with improved power efficiency with good stability. A power output of 16 mW near 60 GHz was obtained with an InP Gunn diode. Q_{ext} was found to be about 400 when the coupling from dielectric image waveguide to metal waveguide (used for power measurement) was adjusted for maximum power transfer, by changing the penetration of the image line into the metal waveguide transition.

Future plans include a study of similar structures using varactor tuning for optimum frequency scan. This approach may be useful for microstrip oscillators where high Q's and adjustability are problems.

APPENDIX A
EQUIVALENT CIRCUITS FOR OSCILLATOR

The analysis presented here is related to microstrip oscillators developed by K. Chang [3] and E. J. Denlinger [4]. We shall use their basic approach and apply it to the Gunn diode in a recessed coaxial metal structure (Fig. 2). The equivalent circuit is shown in Fig. 3, where $-R$ is the negative resistance of the diode, C_j is the junction capacitance, L_p is the package inductance ≈ 0.15 nH, C_p is the package capacitance ≈ 0.12 pF, Z_T is the transformed load impedance, and Z_g is the diode impedance.

Here, R_L is the load resistance which the diode package sees as transformed by the coaxial cavity and image guide. It consists of a coaxial line with a cavity exit (iris) just under the Al_2O_3 image guide (Figs. 2 and 5). Above the iris is a second cavity which is covered with a metal disk located above the alumina waveguide. The energy then propagates down the Al_2O_3 into free space or into the metal waveguide used for measurement of power and frequency. We shall assume that for optimum power transfer, the load R_L that the diode package sees is real. In some cases, the load is not purely resistive as shown, but using the assumption of resistive load one can gain some insight into mechanisms which are occurring. With reference to Fig. 3, if one knows C_p and L_p and the oscillator frequency, C_j can be calculated by equating the imaginary parts of the impedance at the diode chip by

$$-\operatorname{Im} Z_g = \operatorname{Im} Z_T$$

$$-\operatorname{Im}\left(-R - j\frac{1}{\omega C_j}\right) = \operatorname{Im}\left(j\omega L_p + \frac{1}{\frac{1}{R_L} + j\omega C_p}\right)$$

$$= \frac{\omega L_p - \omega C_p R_L\left(R_L - \omega^2 R_L L_p C_p\right)}{1 + \omega^2 C_p^2 R_L^2}. \tag{A1}$$

Therefore, by (A1)

$$\frac{1}{\omega C_j} = \frac{1}{1 + \omega^2 C_p^2 R_L^2}\left[\omega L_p - \omega C_p R_L\left(R_L - \omega^2 R_L L_p C_p\right)\right] \tag{A2}$$

$$C_j = \frac{1 + \omega^2 C_p^2 R_L^2}{\omega^2\left[-C_p R_L^2 + L_p + \omega^2 C_p^2 R_L^2 L_p\right]}. \tag{A3}$$

C_j is calculated using (A3), assuming

$$\omega = 2\pi \times 6 \times 10^{10} \text{ rad/sec}$$
$$C_p = 0.12 \times 10^{-12} \text{ F}$$
$$L_p = 0.15 \times 10^{-9} \text{ H}$$
$$R_L = 250\ \Omega.$$

From (A3) it can be seen that C_j becomes relatively independent of R_L when R_L takes on larger values, i.e., $> 50\ \Omega$. Using these values, $C_j = 0.09$ pF. The criterion for the start of oscillation is

$$|\operatorname{Re} Z_g| \geqslant |\operatorname{Re} Z_T| \tag{A4}$$

where $|\operatorname{Re} Z_g| \cong 8\ \Omega$ for these types of Gunn diodes. From (A4) and Fig. 3

$$Z_g = -R - j\frac{1}{\omega C_j}, \qquad |\operatorname{Re} Z_g| = R$$

$$Z_T = j\omega L_p + \frac{1}{\frac{1}{R_L} + j\omega C_p}$$

$$\operatorname{Re} Z_T = \frac{R_L}{1 + \omega^2 C_p^2 R_L^2}. \tag{A5}$$

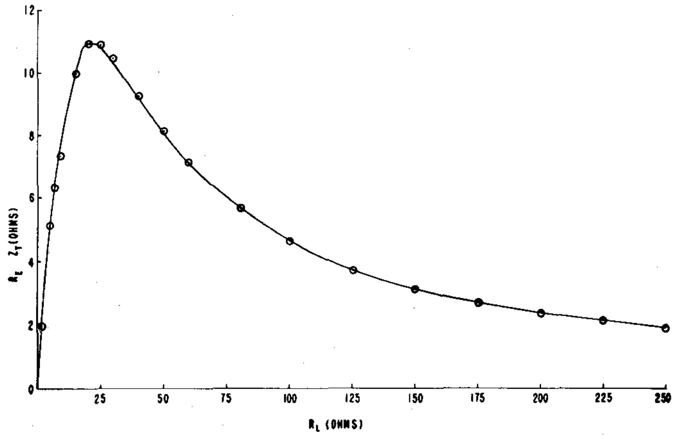

Fig. 11. Re Z_T versus R_L.

TABLE III
COAXIAL LINE IMPEDANCES

Cavity Structure	Cavity Diameter a (inches)	Post Diameter c (inches)	Characteristic Impedance Z_0
G6-1	0.156	0.025	110 Ω
G6-2	0.196	0.025	123 Ω
G6-3	0.250	0.025	138 Ω

By (A4), we require Re Z_T to be small for the onset of oscillation. Hence, a large R_L offers a practical approach. Fig. 11 is a plot of (A5) where Re Z_T is plotted as a function of R_L. It is seen that for R_L greater than 50 Ω, the Re Z_T drops to well below the required values of 8 Ω for the start of oscillations.

APPENDIX B
RESONATOR STRUCTURE

We can look upon this oscillator as a diode feeding into a coaxial line cavity. To do this, consider Fig. 5. The impedance of the coaxial line is calculated using (B1) [7], and tabulated in Table III as

$$Z_0 = \frac{138}{\sqrt{\epsilon_r}} \log_{10} \frac{a}{c}, \qquad \text{for } \epsilon_r = 1. \tag{B1}$$

The dielectric image line with a 0.050-in-diameter hole provides some further guidance to the TEM wave with the top disk acting as a reflecting wall. The top disk also serves as a resonant transformer to launch the electromagnetic energy laterally into the dielectric waveguide in the $E_{11}y$ mode. At resonance, a $\frac{1}{2}\lambda$ coaxial structure exists from the bottom of the coaxial cavity to the bottom of the top disk, the distance being 0.042 in + 0.015 in + 0.040 in = 0.097 in or 2.5 mm for 60 GHz, where cavity height $d = 0.042$ in, metal lip (iris) $e = 0.015$ in, and the dielectric thickness $T = 0.040$ in.

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