Fundamental and Harmonic Operation of Millimeter-Wave Gunn Diodes

WILLIAM H. HAYDL, SENIOR MEMBER, IEEE

Abstract—**Pulsed and CW measurements in the range 26–110 GHz were performed on gallium arsenide (GaAs) Gunn diodes having active lengths of 1.8–2.6 μm, bonded into commercially available packages. The diodes were operated in full-height waveguides in the *V*-(WR-15), *E*-(WR-12), and *W*-(WR-10) bands, using coaxial-bias circuits and a disc-post resonator to provide the required resonance at their fundamental frequency in the range from about 25–65 GHz. Frequency and power measurements were performed up to 110 GHz on the fundamental, second, and third harmonics. The main emphasis of this experimental investigation has been the study of frequency changes caused by changes made in the various parameters of the disc, post, diode, diode package, and embedding waveguide sections.**

I. Introduction

THE GUNN DIODE is one of the most important solid-state millimeter-wave sources. It exhibits low FM noise and a wide operating frequency range, and is therefore extensively used as a local oscillator. The Gunn (or transferred-electron) effect has been observed in a number of III–V materials and compounds. However, only gallium arsenide (GaAs) and indium phosphide (InP) seem to be of significant importance for practical devices. In the past, theoretical treatments have attempted to define an upper frequency limit for Gunn diodes [1]–[3]. It seems that these predictions are not precise enough to estimate the achievable RF power in the range of 30–150 GHz, and it appears that this information can only be obtained from experimental results. With continuing improvements in material technology [4], packaging, and oscillator design, statistical data accumulates which will be useful in exploring the upper frequency and power limits of Gunn devices.

Useful RF output powers from Gunn diodes have been observed in the 95-GHz range as early as 1975 [5]. It has not been until very recently that it was recognized that such frequencies are realizable in GaAs Gunn diodes only by second harmonic operation [6]–[9]. Fundamental as well as harmonic operation of Gunn diodes has, however, been observed for over a decade now, but mostly at low frequencies [10]. Computer simulations and measurements on Gunn diodes have shown that these devices exhibit highly nonlinear current and voltage waveforms, containing strong harmonic components [11]. It is thus desirable to identify fundamental and harmonic operation of these devices. Since their power output in the fundamental mode decreases rapidly with increasing frequency, useful harmonic power may still be available at frequencies not attainable in the fundamental mode.

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The author is with the Fraunhofer-Institut für Angewandte Festkörperphysik, Eckerstrasse 4, D-7800 Freiburg, West Germany.

II. The Gunn Diodes

Gunn diodes are transit-time devices which are capable of operating over very wide frequency ranges around the transit-time frequency, if placed in the proper circuit. Gunn diodes exhibit only very limited voltage tuning, but when placed into a resonant circuit, they can be tuned over as much as 50 percent around their transit-time frequency. We have investigated diodes with active lengths l_d in the range of 1.8–2.6 μm. The GaAs epitaxial material was grown by vapor-phase epitaxy (VPE) and by molecular beam epitaxy (MBE). The active GaAs n-type epitaxial layers were grown with and without n^+-contact layers on n^+-substrates with n^+-buffer layers. Our devices had the parameters

$$nl_d \cong 2\times 10^{12}\ \mathrm{cm}^{-2}$$

where n is the carrier density of the active epitaxial (n) layer of thickness l_d. The nl_d product lies above 1×10^{12} cm^{-2}, the value above which instabilities occur.

The diode package can be considered to be an integral part of the diode. One commercially available package has found widespread use [12]. Although this package has large parasitic elements for the frequencies considered, it has been used by us in our experimental studies, because the majority of commercially available Gunn diodes are making use of it.

Our studies are concentrating on GaAs Gunn diodes with active lengths l_d in the range of 1.5–2.5 μm, with expected transit-time frequencies of about 35–55 GHz. Details of our diodes are listed in Table I.

III. Millimeter-Wave Gunn-Diode Circuit

In the past, millimeter-wave devices have been operated in waveguide circuits in a number of different ways. Some of the more popular methods are illustrated in Fig. 1. The inductive post coupling in Fig. 1(a) using a full- or reduced-height waveguide has been used extensively for Gunn diodes at the lower frequencies [13]. Reduced-height waveguide mounts as shown in Fig. 1(b) have been used frequently for millimeter-wave IMPATT diodes in order to reduce the post inductance and to achieve a better impedance match to the low-impedance diode [14]. Frequency tuning is possible by means of the backshort for Fig. 1(a)

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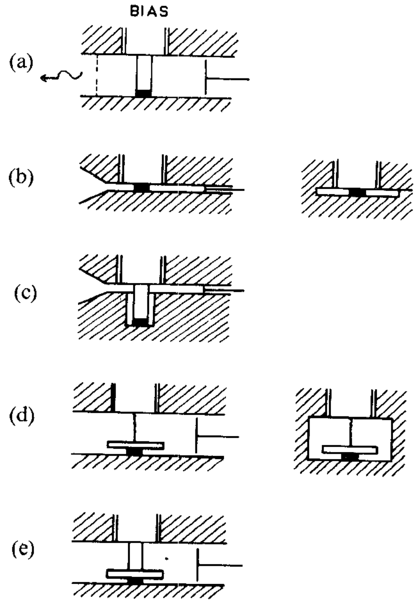


Fig. 1. Various waveguide oscillator configurations used at microwave and millimeter-wave frequencies. (a) Inductive post (and iris). (b) Reduced-height waveguide. (c) Waveguide with coaxial resonator. (d) Disc. (e) Disc with bias post.

TABLE I
GaAs Gunn Diodes Used

No.	n (10^{16} cm^{-3})	l_d (μm)	I_{th} (A)	bond
GD-1	0.9	2.1	0 9	single
GD-3	0 9	2 1	1 0	cross
GD-4	0.9	2.1	variable	single
GD-6	0 9	2 1	0 8	cross
GD-7	1.0	1.8	1.2	cross

standard F-8 package (12) with C_p 160 fF

and (b). The circuit illustrated in Fig. 1(c) has been used for millimeter-wave IMPATT diodes. The frequency is determined by the dimensions of the coaxial resonator, and the power output by the position of the short. In the past, millimeter-wave IMPATT diode oscillators have also been using discs [15], [16] with a high-inductance bias lead as illustrated in Fig. 1(d). Here, the diode and the disc transmission line form a resonator and an impedance transformer. The disc diameter has a significant effect on the frequency and power output.

Gunn-diode oscillators have been operated in circuits illustrated in Fig. 1(e) in the frequency range of 60–140 GHz [4]–[9], [17]. The dimensions of the inductive post above the disc are such that there is a resonance in the range of 30–60 GHz at which the Gunn diode may operate [18]. It has, therefore, not always been clear in the past if diodes have operated in the fundamental or harmonic mode [5]. It is this circuit which has been investigated by us, and it is one of the aims of this paper to describe the effects of the device and package parameters, as well as those of the microwave circuit on the performance of Gunn oscillators at the fundamental, as well as the harmonic, frequencies. The main emphasis of our investigation has

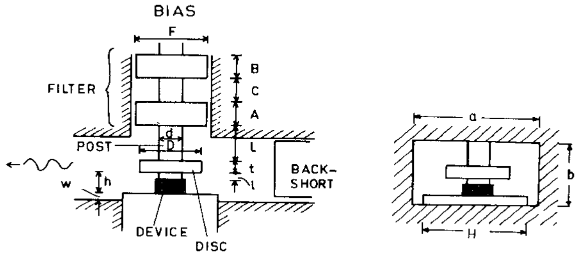


Fig. 2. Schematic representation of a Gunn oscillator with coaxial bias circuit and disc-post resonator, as it is used in this experimental investigation.

been on determining the effects of the various parameters on the oscillator frequency, and to a lesser extent on the RF power.

In Fig. 2, we have illustrated the millimeter-wave Gunn-diode circuit used for this study. It consists of a device on a heatsink, a small post of diameter d and length l above the diode package, a disc of diameter D and thickness t, a post of length L and diameter d connecting the disc and the bias-line filter, and finally the bias-line filter itself.

Though a number of dimensional parameters determine performance, very little is known about their function and their effect on frequency and RF power output. An approximate equivalent circuit is shown in Fig. 3. The diode is represented by a negative resistance $-r$, positive parasitic resistances R, and diode capacitance C_d. The package parameters are the bonding lead inductance L_b and the package capacitance C_p. The disc and the bottom of the waveguide form a radial waveguide [16], [19] of radius $D/2$. The inductance of the post is L_L. The waveguide dimensions may be chosen such that its cutoff frequency f_c lies below or above the fundamental operating frequency of the diode. In the space between diode and short, a resonance is possible if f_c lies below the fundamental diode frequency. Additional resonances are possible involving the lumped inductances and capacitances. In our experimental investigations, the waveguide cutoff frequency was generally chosen to lie above the oscillator fundamental diode frequency. This frequency is determined primarily by the diode parameters and the circuit parameters L_L, L_b, C_p, C_d, and the radial disc impedance at the fundamental frequency f_1.

The conditions for circuit-controlled oscillations have been treated by a number of authors and are restated here only for reference

$$R_{\text{diode}}(f)+R_{\text{circuit}}(f)=0 \tag{1}$$

$$X_{\text{diode}}(f)+X_{\text{circuit}}(f)=0 \tag{2}$$

$$\frac{\partial X_{\text{total}}}{\partial f}>0 \tag{3}$$

where f indicates frequency.

Theoretical and experimental investigations on a number of different radial-line configurations [19], [20] indicate a susceptance of the disc B_D as shown in Fig. 4. This impedance of a disc only, as seen from the diode (package) terminals, is capacitive at low frequencies and inductive at higher frequencies.

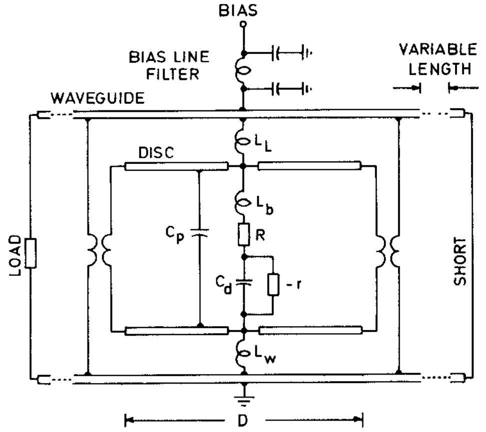


Fig. 3. Approximate equivalent circuit of the Gunn diode and disc-post resonator illustrated in Fig. 2. C_d is the diode capacitance, C_p the package capacitance, L_L the post inductance, L_b the bonding lead inductance, R the parasitic diode positive resistances, $-r$ the negative diode resistance, and D the disc diameter.

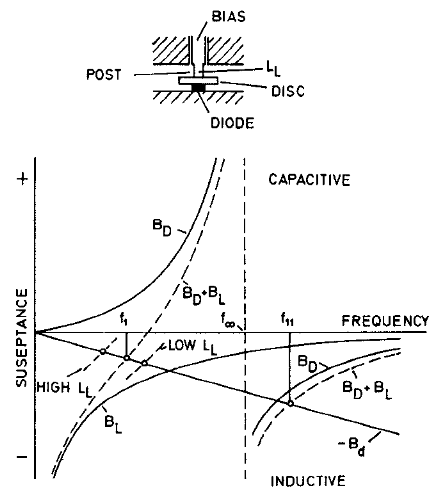


Fig. 4. The graphical solution of (2). Two oscillation frequencies f_1 and f_{11} are possible at the intersection of the diode susceptance ($-B_d$) and the disc and post susceptances ($B_D + B_L$, dashed curve).

A practical circuit is illustrated in Fig. 4. A post inductance L_L is now introduced, which alters the total susceptance seen by the diode as indicated by the line $B_D + B_L$, and results in two oscillation conditions, one at f_1 and another at f_{11} at the intersection of the curve $B_D + B_L$ and the diode susceptance line B_d (see (2)). For very high values of $L_L (B_L = 0)$, only one resonance exists at f_{11} as described above (see also Fig. 1(d)). There exists an upper limit for the frequency f_1, which is designated f_∞. For V- and W-band oscillators with typical disc diameters of 3 to 1.5 mm, f_∞ is of the order of 30–60 GHz, respectively [18]–[20]. If (1) is satisfied, oscillations will take place at one of the frequencies f_1 or f_{11}. Gunn diodes as described in this paper are operating in the mode f_1, which corresponds to their fundamental frequency of 25–65 GHz. For simplicity, the package capacitance is included in the diode susceptance B_d, and the bonding lead inductance L_b has been assumed to be zero. Oscillations are then possible at f_1, according to (2), if (1) is satisfied. An increase in the diode or package capacitance (an increase in the slope of B_d) will result in a lower oscillation frequency f_1. An increase in the disc diameter will result in a shift of the disc susceptance towards lower frequencies, and hence in a decrease in f_1.

TABLE II
RESONATOR DIMENSIONS (mm)

resonator no	D	d	L	l	t	A	B	C	F
A	VAR	0.50	0.45	¯0 28	0.31	0 85	0 85	0 85	2.8
B	VAR	0.50	0.45	0	0.31	0 85	0.85	0.85	2.8
C	VAR	0.50	0.43	0	0.18	0.89	0.83	0.90	2.8
D	VAR	0 50	0.65	0	0 31	0 65	1.06	0 69	2.8
E	1 72	0.30	VAR	0	0.30	5	0	5	2.8
F	2.00	0.50	VAR	0	0 30	1.50	0	1.50	2.8
H	1 90	0 52	0.44	VAR	0.22	0.90	0.85	0.90	2.8
I	1 90	0.52	0.45	VAR	0 30	0.88	0.84	0.90	2.8
J	1.90	0.52	0 75	VAR	0 30	0.57	1 15	0.59	2.8
K	1 48	0 51	0.74	0	VAR	0 56	0.86	0.90	2 8
L	1 89	0 51	0.75	0	VAR	0 59	0.87	0 90	2 8

VAR indicates "variable"
RES B-1.7 indicates "resonator B with disc diameter 1 7 mm"

Radial lines generally have the form of a disc. In practice, such a radial symmetry does not seem to be of great importance. Vane-type circuits have been operated successfully in the past. Diode packages, such as quartz standoffs, have no circular symmetry, and devices are not always located exactly in the center of the radial line. Furthermore, theoretical and experimental evidence indicates little difference between circular and square geometries [19].

With reference to Fig. 2, it is to be expected that the resonant frequency of this circuit containing the device must be affected by changes in the various reactive elements, hence the dimensional parameters of the circuit and the device itself, as well as the package. We have experimentally determined these frequencies for GaAs Gunn diodes. The results are presented below. The large dimension of the waveguide generally sets an upper limit for the disc diameter. A lower limit is set by the package diameter. A number of different coaxial radial lines were used in this experimental study. Their dimensions are listed in Table II.

IV. FREQUENCY MEASUREMENTS

A schematic representation of the measurement system used is shown in Fig. 5. Oscillator sections containing the diode–disc-post bias filter assembly were constructed using W-, E- and V-band waveguide sections. The lengths were kept between 5 and 10 mm, in order to be able to couple out the fundamental frequency components in the range of 25–60 GHz, which sometimes lie below the waveguide cutoff frequencies. The signals were detected by attaching waveguide measuring systems with tapered transitions to the oscillator sections. Since the fundamental power is of the order of 10 dB above the second harmonic power, it can be monitored in most cases simply by placing the measurement system (with or without a horn) near one of the oscillator output ports or near the bias line, which was always unshielded and designed to be effective only at the harmonic frequency of interest (see Table II). All waveguide ranges down to Q-(WR-22) and Ka-(WR-28) band were available. Broad-band isolators were used for all

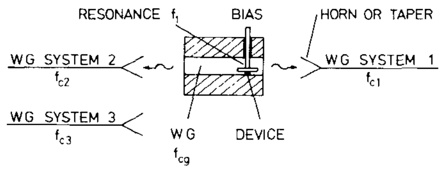


Fig. 5. Schematic representation of the experimental waveguide system used for determining the fundamental and harmonic frequency components of a Gunn-diode oscillator. The waveguide cutoff frequencies are indicated by f_c.

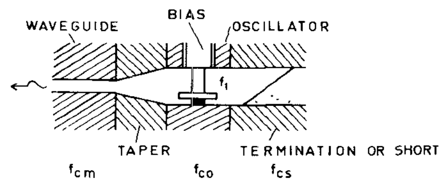


Fig. 6. Typical experimental oscillator consisting of several sections, with cutoff frequencies f_c.

measurements close to the oscillator section in order to minimize reflections and unwanted resonances. The diodes were operated in a pulsed mode (150-ns pulsewidth 1.3-MHz repetition rate) as well as in CW. Our oscillators consisted of several sections as, illustrated in Fig. 6. Different size waveguides were used for the measurement system (output section), the oscillator section, and the backshort section having the cutoff frequencies f_{cm}, f_{co}, and f_{cs}, respectively. Tapers were employed to minimize reflections and the possibility of having more than one resonant frequency present in the system. The propagation of the fundamental frequency within the waveguide can be eliminated by choosing the cutoff frequency of the oscillator section to lie above the fundamental frequency and below the desired harmonic frequency component. A W-band waveguide is ideal for an oscillator with $f_1 = 45$ and $f_2 = 90$ GHz, since $f_{co} = 59.4$ GHz. Thus the fundamental is reactively terminated and remains confined to the diode–disc-post assembly. As we shall show below, an increase in the waveguide dimension of the oscillator section, causing f_{co} to lie below f_1, will cause erratic oscillator behavior.

V. Variation of Disc Diameter D

The qualitative change of the disc susceptance B_D (see Fig. 4) with frequency and disc diameter has been reported [19], [20]. The frequency f_∞ at which B_D changes from capacitive to inductive increases with decreasing disc diameter. The intersection of the diode and circuit (disc and post) susceptances determines the oscillation frequency f_1 of the diode, as given by (2).

The effect of varying the disc diameter D on the frequency is illustrated in Fig. 7 for a series of four-resonator sets of varying diameters, with Gunn diode GD-1 in a W-band waveguide section. The waveguide cutoff frequency is 59.4 GHz, and the fundamental oscillation frequency range is 39–55 GHz. In Fig. 7, we have monitored only the second harmonic frequency. Resonator D has a longer section L than resonators A, B, or C, and thus a higher inductance L_L, hence a lower resonant frequency. Resonator C has a thinner disc than A and B, hence a slightly lower fringe capacitance at the disc periphery, and thus slightly higher frequencies than A and B.

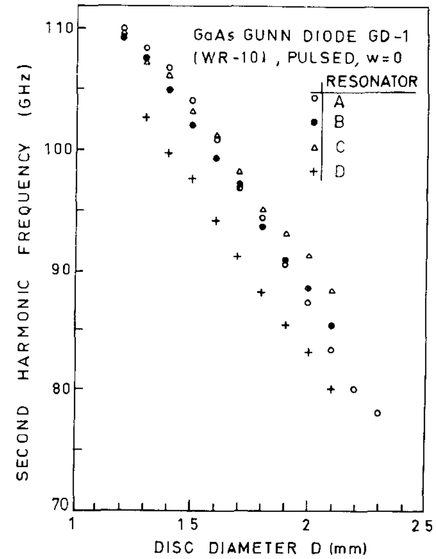


Fig. 7 Effect of disc diameter D on the oscillator frequency with Gunn diode GD-1, for a series of four different disc-post resonators, in W-band waveguide.

The rate of frequency change observed is approximately 33 percent/mm. The measurements were made with the backshort and bias voltage optimized at each data point. The frequency change with bias voltage is small, generally less than 0.5 GHz. The use of bias-voltage tuning as an additional means for identifying fundamental and harmonics has been described in [7]. Since the waveguide cutoff frequency is well above the fundamental frequency, the backshort has no effect on the frequency as we shall also show. The measurements were made under pulsed conditions. The second harmonic frequencies for CW operation are typically 2.5 GHz lower (2.5 percent).

The W-band waveguide oscillator had 3-mm-diam holes to accommodate the diode, including the heatsink and the disc-post-bias filter assembly. Discs up to 2.8-mm diam and radial lines with and without $\lambda/4$ filter sections (at the second harmonic frequency) were used.

The fundamental, second, and third harmonic frequencies of diode GD-1 as a function of disc diameter D are shown in Fig. 8, for two different resonators. The data clearly indicates the wide range of the fundamental frequency. The diode had its peak RF power output at about 47 GHz. The second harmonic RF power had its peak at 94 GHz. The data of Fig. 8 was obtained by the method illustrated in Figs. 5 and 6. Power levels were low, since the oscillator section was terminated in both directions in the waveguide measuring systems. Since both the second and the third harmonic frequencies entered the W-band detector, with the second harmonic power level being about 10 dB above the third, an E-H tuner was used to detune the second harmonic, and allowed the third harmonic to be detected. Power levels at the second harmonic frequency of 94 GHz have been as high as 20 mW (CW operation) when using a backshort. The same

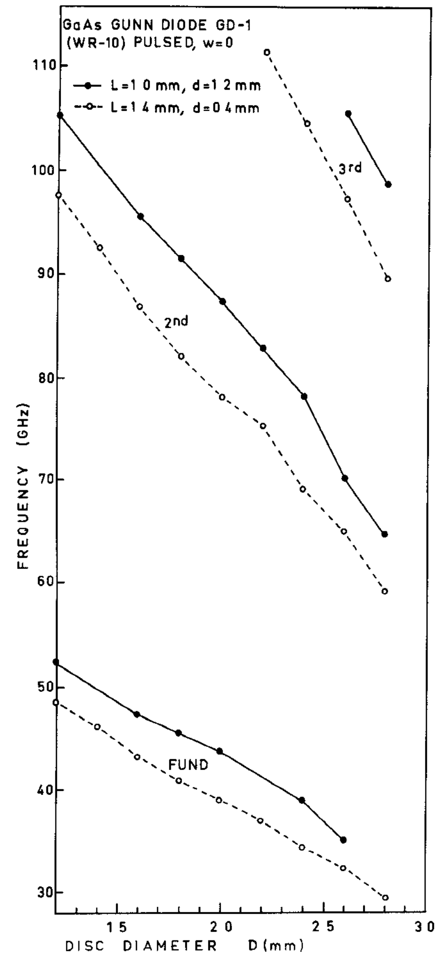


Fig. 8. Variation of the fundamental, second, and third harmonic frequencies with disc diameter D ($t = 0.2$, $l = 0$, and $F = 2.8$ mm).

diode, GD-1, delivered 120 mW in a fundamental frequency oscillator at Q-band.

VI. Variation of Disc Thickness t

The effect of the thickness t (and h) of the disc on the frequency has been discussed elsewhere [16] in terms of an effective increase of the disc radius with increasing t (and h), due to the fringing fields at the edge of the disc. Thus the effective electrical length of the radial line is larger than its physical length (radius $D/2$), and increases with t and h. Our experimental results of the frequency behavior with disc thickness t are illustrated in Fig. 9. The experimental conditions were identical to those of Fig. 7. The observed rate of decrease in frequency with increasing t is about 15 and 25 percent/mm for the small and large disc diameter, respectively. This agrees well with a calculated value [16] of 25 percent/mm ($h = 0.275$ mm).

VII. Variation of Post Length L

A decrease of the fundamental resonant frequency, and hence the observed harmonic frequency, is expected with increasing post length L, since this results in an increased inductance of the resonant circuit. Using two different resonators with variable L, having the form of a variable coaxial short, the observed second harmonic frequency

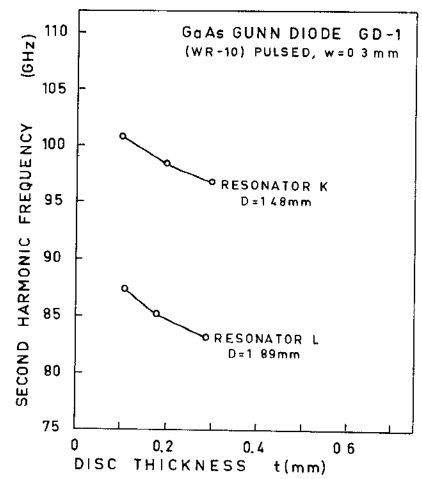


Fig. 9. The variation of the second harmonic frequency f_2 with disc thickness t.

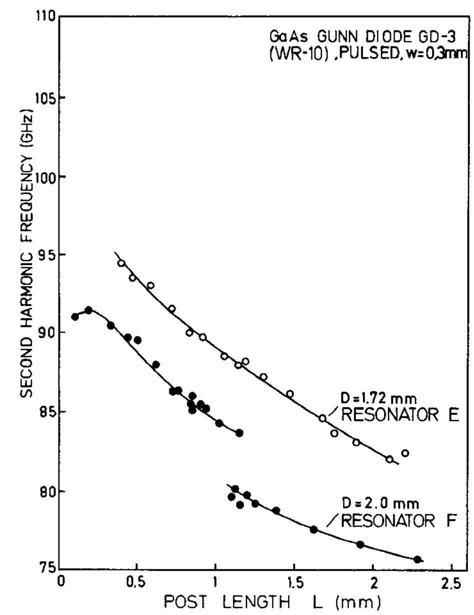


Fig. 10. Frequency variation with bias post length L.

varies with L as is illustrated in Fig. 10. There exists a maximum attainable frequency for low L or low L_L, and the rate of change varies with L_L as predicted from Fig. 4. The observed discontinuity may be caused by the nonlinearity of the diode and the existence of other resonances [13].

VIII. Variation of Post Diameter d

Varying the post diameter d also has a pronounced effect on the frequency. Measured results with diode GD-3 in V- and W-band waveguides, where again tapers were used for the measurements, are illustrated in Fig. 11. Two different disc diameters D were investigated, with the post diameter d varying from the value of D to about 0.3 mm. The fundamental, as well as the harmonic, frequencies were measured. The frequency is observed to decrease with decreasing post diameter d, which is consistent with the effect of an increasing inductance L_L. The rate appears to

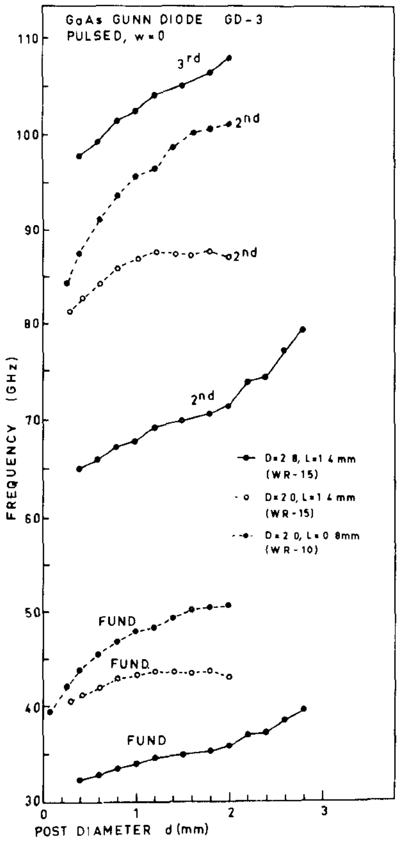


Fig. 11. Frequency variation with bias post diameter d for several resonators in V- and W-waveguide sections ($t = 0.3$, $l = 0$, and $F = 2.8$ mm).

be larger for smaller values of D. Within certain ranges of d, a constant oscillation frequency, which is independent of d, is observed. This is believed to be due to the fact that the fundamental frequency lies above the waveguide cutoff frequency of 40 GHz for the V-band oscillator. For the V-band oscillator with fundamental frequency below the waveguide cutoff frequency of 40.1 GHz, and for the W-band oscillator with fundamental frequency below its cutoff frequency of 59.4 GHz, the frequency continuously increases with increasing post diameter d. It should also be observed from Fig. 11 that the second harmonic frequency increases at a higher rate with increasing d for the resonators with smaller post length L.

IX. Variation of l

An increase in l, the length of the post section between diode and disc, causes a reduction in the impedance transformation ratio, because of an additional inductance in series with the diode. As a result, a sharp reduction in RF output power is expected with increasing l, which we have observed experimentally. The observed frequency variation with l is illustrated in Fig. 12. The effect of the parameter w, the distance where the post containing the diode protrudes into the waveguide, is also shown. Varying the height of the diode-bias line assembly within the waveguide had little effect on the frequency. A small decrease is observed with increasing w. The diameter H of the diode heatsink in all our experiments was 3 mm.

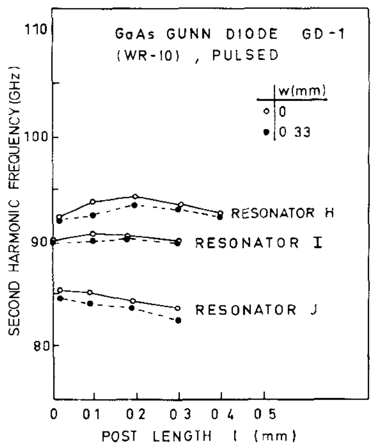


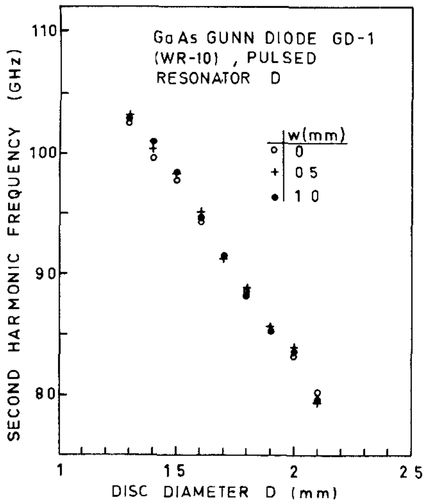
Fig. 12. Frequency variation with post length l and diode insertion parameter w.

X. The Effect of the Waveguide

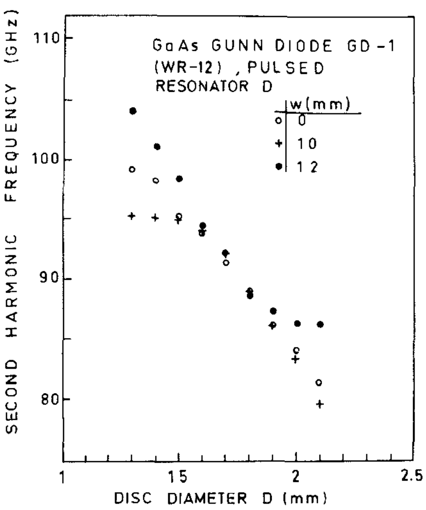
In the following three illustrations, the effect of the parameters waveguide cutoff frequency, diode fundamental frequency, and diode insertion depth w is shown. Using a series of resonators with varying diameter and a 2-μm Gunn diode in a W-band oscillator section, with the backshort replaced by a termination, the second harmonic output frequency varies linearly with disc diameter D, as illustrated in Fig. 13(a). The effect of w is negligible. The fundamental frequencies (40–52 GHz) lie well below the waveguide cutoff frequency of 59 GHz. The effect of going to a larger waveguide, to E-band with the same set of resonators, is illustrated in Fig. 13(b). A taper was used to couple to the WR-10 waveguide detection system. For low values of w, the frequency does not vary linearly with D, when the fundamental frequency is above the waveguide cutoff frequency of 48.5 GHz. This effect can be seen in a different form in Fig. 13(c) with resonator D, which had a longer post length L. For $w = 0$, the departure from a linear variation of f_2 with D occurs in (b) and (c) above 96 GHz ($f_1 = 48$ GHz), which coincides with the cutoff frequency of the waveguide. If the diode is inserted more deeply into the waveguide, the departure occurs at a lower frequency, presumably because of the great distortion resulting from the diode post in the waveguide.

XI. The Bias-Line Filter Section

The filter section should ideally be a low-pass filter of narrow bandwidth (several GHz) having a stopband reaching up to 200 GHz or higher. Such a filter does not seem to be possible in practice. Investigations on coaxial-type filters, consisting of several high- and low-impedance sections, fractions of a wavelength long, have shown that they exhibit anomalous passbands (or resonances) in the theoretical stopband region. For millimeter-wave devices, a practical filter should exhibit stopbands at the operating frequencies, which in our case are two or more frequencies. In addition, the filter should be able to suppress low-frequency oscillations appearing at the bias-line terminals in the range of 10–100 MHz.



(a)



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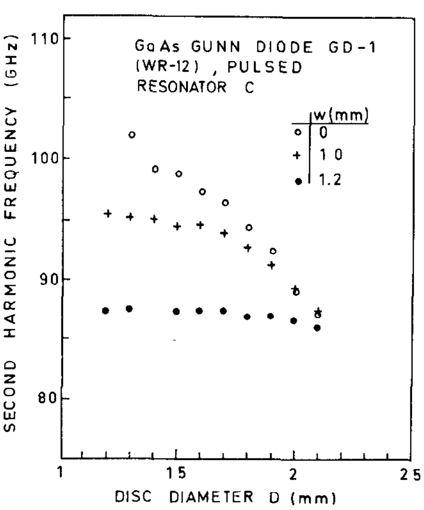

(c)

Fig. 13. (a) Second harmonic frequency variation with disc diameter D and waveguide insertion parameter w of a diode in W-band waveguide, when the fundamental frequency f_1 lies below the waveguide cutoff frequency (59.4 GHz). (b) and (c): Second harmonic frequency variation with disc diameter D and diode insertion parameter w for two different sets of resonators in E-band when the fundamental frequency does not lie much below the waveguide cutoff frequency (48.5 GHz).

With reference to Fig. 2 and Table II, most resonators used had a filter section consisting of $\lambda/4$ sections at 90 GHz, and not at the fundamental oscillation frequency, around 30 or 45 GHz. It is, therefore, reasonable to assume that the filter section must have some effect on the resonance frequency of the entire circuit, adding capacitance and thus decreasing the resonance frequency. Our experimental results seem to confirm this, and indicate that at least the dimension A, through its capacitance, affects the oscillation frequency of the Gunn diode.

Keeping all other parameters constant, and only reducing the dimension A, the width of the first $\lambda/4$ section (by increasing dimension C), an increase in the second harmonic frequency from 94.5 to 96 GHz (1.5 percent) was observed. The results indicate that this first section of the filter contributes to the total capacitance of the resonant circuit, which determines the fundamental oscillation frequency.

XII. The Diode Capacitance C_d

From Fig. 4, one may deduce that a change in the diode capacitance (slope of B_d) will change the circuit resonance frequency f_1. We have verified this experimentally by varying the active cross section of a Gunn diode by chemically etching a packaged device (without cover) successively smaller, and monitoring the diode current, especially the threshold current. The diode capacitance C_d and the threshold current I_{th} are related through the expression

$$I_{th} = D_d^2\left(\frac{\pi}{4}\right)E_{th}nqu = C_d\frac{l_d E_{th} nq\mu}{\epsilon_0\epsilon_r} \qquad (4)$$

where E_{th} is the threshold field for the Gunn effect in GaAs (3×10^3 V/cm), n the carrier density, q the electronic charge, μ the electron mobility, l_d the diode active length, and ϵ_r the dielectric constant. Equation (4) is also useful in order to estimate the carrier density of a diode, since this is one of the material parameters which is generally difficult to determine. Experimental results of the second harmonic frequency change with diode threshold current, and thus diode area or capacitance, and are illustrated in Fig. 14 for diode GD-4. The range of 2.3 to 0.6 A in threshold current corresponds to a calculated change in capacitance from 550 to 250 fF, or a change in diode diameter from 125 to 65 μm.

XIII. The Package Capacitance C_p and Bonding Lead Inductance L_b

We have used commercially available packages [18] consisting of an alumina ring of 0.8 mm outside and 0.37 mm inside diameter and 0.27-mm height, having a dielectric constant of about nine. The ceramic rings are mounted on a 3-48 UNC-2A gold-plated copper screw. The integral heatsink of the diodes is typically 30 μm of plated gold. The diodes were soldered into the packages with gold–tin alloy and contacted with 13×50-μm gold ribbons. Either one ribbon (single) or two ribbons (cross) were placed over the diode and attached to the top of the alumina ring by thermal compression bonding. The diodes were then etched

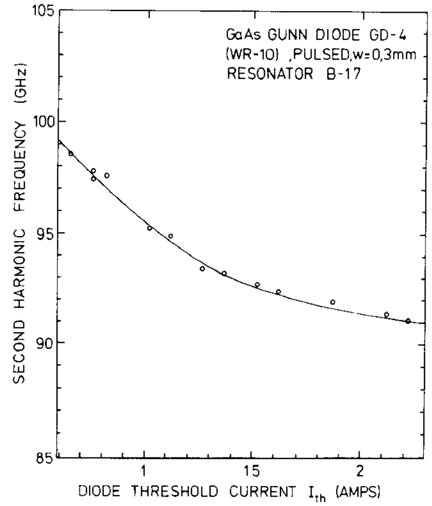

Fig. 14. Frequency variation with diode threshold current I_{th} which is linearly related to the diode capacitance C_d and the diode area.

chemically to the proper cross sections, and a 50-μm-thick gold disc was soldered to the top of the package. The package had a capacitance of about 160 fF. A reduction in the capacitance of the resonant circuit will increase its frequency. Thus a reduction of the package capacitance C_p should result in an increase of the fundamental oscillator frequency f_1, and of its harmonics. This was verified by removing part of the ceramic ring of the package, leaving two standoffs. The reduction of package capacitance from 160 to 50 fF caused an increase in the second harmonic frequency (WR-10 waveguide) from 95 to 103 GHz (8 percent) for diode GD-5, using resonator V-1.7. Similarly, an increase in the frequency is expected if the bonding lead inductance L_b is reduced. A second harmonic frequency increase of 3 GHz at 96 GHz (3 percent) was observed when the single ribbon was changed to a cross ribbon on the diode and package.

The inductance of the bonding wires will effect the oscillation frequency as well as the output power. Our experimental observations indicate that a reduction of the lead inductance L_b seems to be of much greater importance than a reduction of the package capacitance C_p for optimizing the power output.

XIV. The Backshort Section

The cutoff frequency of the backshort section with respect to the fundamental frequency of the diode may affect the frequency behavior of the oscillator. By adding a backshort section in which the fundamental may propagate, a second possible resonance is introduced. Such an oscillator may exhibit limited frequency tuning of about 1–3 percent by means of the backshort. Our experimental results are illustrated in Fig. 15, where the diode was placed in an E-band section with an E-band short, and the output section was tapered to W-band. In the past, such tuning discontinuities have been observed to exist in Gunn-diode oscillators and are an indication that several resonances are present, and are believed to be caused by the nonlinearity of the diode [13].

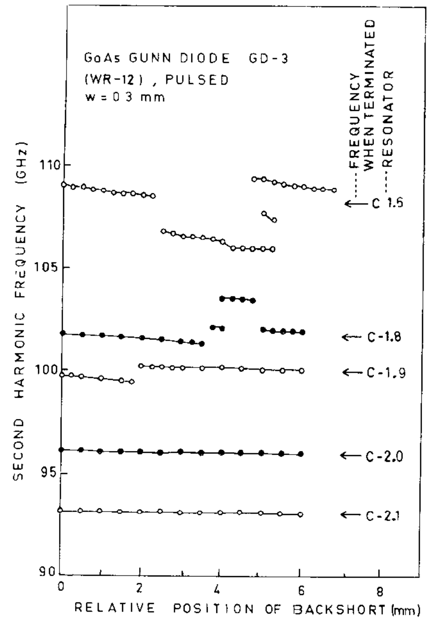

Fig. 15. Effect of backshort section on the tuning properties of the oscillator. (Frequency jumps occur when the fundamental frequency f_1 of the diode lies above the cutoff frequency of the waveguide (48.5 GHz). The arrow indicates the frequency of the oscillator when the short is replaced by a termination).

If the fundamental frequency f_1 of the diode lies below the cutoff frequency f_{cs} of the backshort section, the oscillator frequency is independent of the position of the position of the backshort, which now serves only to optimize the harmonic power output.

The experimental results with the Gunn diode in a V-band waveguide section with V-band backshort and output taper to W-band, were very much similar to those illustrated in Fig. 15, with the exception that the transition to backshort independent tuning occurred at a lower frequency corresponding to twice the cutoff frequency of the V-band waveguide, and that the frequency jumps were greater.

The observed shift in frequency when a diode is placed from a W-band waveguide into a V-band waveguide is not significant. The observed value with diode GD-3 was +1.2 GHz ($w = 0$, $D = 2$ mm, $d = 0.35$ mm, $t = 0.2$ mm, $L = 1.4$ mm) for the second harmonic frequency of 80 GHz.

XV. RF Power Measurements

The effect of changes in the dimensional parameters on the frequency has been described above. However, the requirements for an oscillator are generally such that the attainable RF power at a given frequency should be maximized. The RF power output has been measured in our experiments, and is illustrated in Figs. 16–18. The data should be used only in a comparative and qualitative manner, since absolute power levels are highly dependent on the particular diodes used, as well as on nonreproducible parameters such as contact resistance in the waveguide circuit. The RF power distribution versus frequency of a Gunn diode is highly sensitive to the active length of the

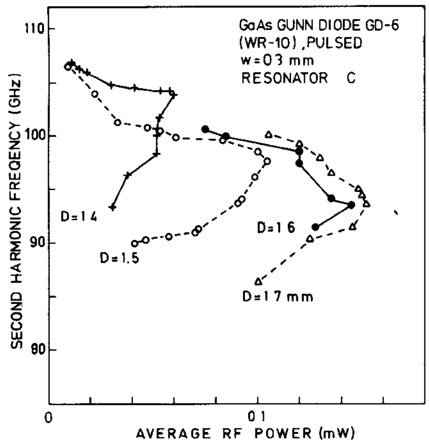

Fig. 16. Capacitive tuning curves for several resonators with discs of different diameter.

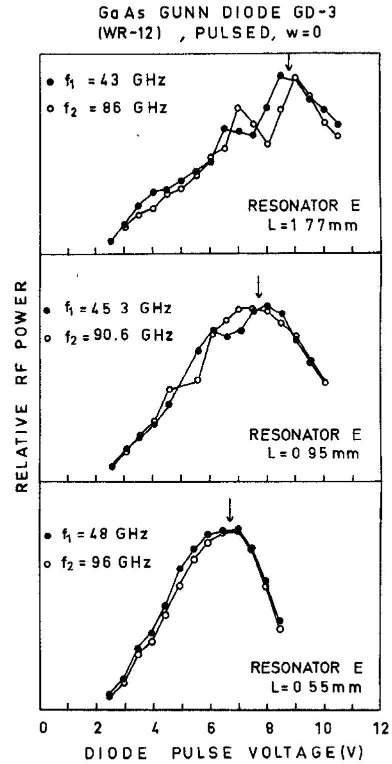

Fig. 17. Fundamental (f_1) and second harmonic (f_2) power output of a pulsed Gunn diode in an E-band waveguide. (Note that f_1 is always below the cutoff frequency of 48.5 GHz. The maximum of the curves has been adjusted to the same value in order to display the variation at f_1 and f_2. The vertical scale is linear.)

epitaxial semiconductor. The thickness of an epitaxial layer may vary across a wafer, depending on the method of epitaxial growth, by as much as 10–30 percent. This will result in a corresponding variation in the frequency at which maximum RF power is obtained, since Gunn diodes are transit-time devices. The exact relationship between the length of the active layer and the frequency at which the RF output power distribution has its maximum is still subject of our investigations, especially for the range 1–2 μm or 50–100 GHz.

Since the height of the package ceramic ring determines the minimum height of the radial cavity, increasing the cavity height is only possible by adding a post of length l, and hence a series inductance. This, however, causes a power output reduction and is undesirable. Higher power output was obtained in our experiments with $l = 0$, indicating that it might be advantageous to reduce the cavity height even further.

Because of the many bandwidth-limiting elements in an oscillator, such as the backshort and the fundamental frequency disc-post resonant circuit, the true power versus frequency distribution of a device cannot be obtained in a simple manner. Since the power output of an oscillator is dependent on the diode power spectrum, disc response, and backshort response, we have developed a method to eliminate the latter two responses, the result being what is believed to be the power-frequency distribution of the Gunn diode.

Experimental results are illustrated in Fig. 16, with several different resonant discs of varying diameter D, continuously tuned by means of a metal tuning pin, as described in more detail in [7]. The metal pin is brought in close proximity to the disc periphery, thus increasing the disc capacitance and hence the fundamental oscillation frequency. The output power should not be greatly affected by this tuning method. The power at each frequency was optimized by means of the backshort. Identical results are obtained at a reduced power level, by replacing the backshort by a termination. The envelope of these individual responses is believed to be very close to the true RF power spectrum of the diode. Without capacitive tuning, only the first data point (highest frequency) of each curve is obtained, indicating for the case of Fig. 16 that the disc diameter is too small. The capacitive pin tuning reduces the frequency, and thus the electrical length, of the disc radial line until optimum conditions (peak RF power) are obtained. Other results illustrating fundamental and harmonic RF power output versus frequency up to 110 GHz have been published elsewhere [21].

In order to gain more insight into the source of the harmonics, both the fundamental and one of the harmonic powers were monitored simultaneously. Of particular interest were the variations of the individual RF powers, and in particular their rate of change with a parameter such as the applied voltage.

Since the applied voltage affects the power, and, to a lesser extent the frequency, care was exercised to maintain a reflection-free broad-band waveguide system. An oscillator waveguide section must be chosen having a cutoff frequency above the fundamental operating frequency f_1 of the oscillator. By placing two different waveguide detection systems (Fig. 5) on either side of an oscillator section, it is possible to monitor the fundamental and the harmonic frequencies. Experimental results of pulsed measurements are illustrated in Fig. 17, where the average RF output power of the pulsed diode was measured as a function of the pulse voltage. Using three different resonators, the diode was operated in an E-band oscillator section with tapers to Q- and W-band measuring systems, in order to

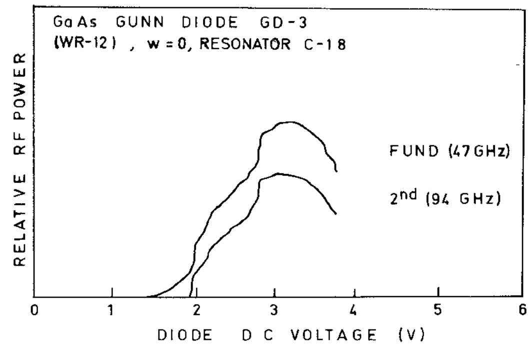

Fig. 18 Fundamental (f_1) and second harmonic (f_2) RF power output of a CW Gunn diode in an E-Band waveguide. Experimental conditions were the same as for Fig. 17.

eliminate unwanted resonances. The bias post length L was varied in order to change the frequency. From the data, it is apparent that the power at the fundamental and at the second harmonic follow each other closely. The peaks occur at the same voltage, and the rates of change with applied voltage are identical. Clearly observable is the behavior of the required pulse voltage for maximum power output. This voltage decreases with increasing frequency. DC measurements made on the same diode are shown in Fig. 18, and indicate identical fundamental and second harmonic RF power output variation versus applied dc voltage. The absolute power levels of the fundamental and the harmonic were low since terminations were used, and differed by 6–10 dB. In Figs. 17 and 18, the RF powers were plotted on a linear scale with equal peak values, for comparison only.

A phenomenological explanation for the observed changes in fundamental and second harmonic power can be given if we consider the source of the harmonic to be due to the RF current and voltage distortions caused by the electron and electric field dynamics inside the device. Representative calculations of device current waveforms for both Gunn and IMPATT diodes have also been made in the past [11]. A change in applied voltage does not cause significant changes in the current and voltage waveforms, but simply increases their amplitude. As a result, all frequency components will change by about the same amount, as is observed experimentally.

The required bias voltage for maximum RF power as a function of frequency, as is illustrated in Figs. 17 and 19, is consistent with observations made in the past on diodes operating in their fundamental frequency mode [22]. This behavior indicates a thermally limited operation in the accumulation layer space-charge mode [23]. The required operating voltages for peak RF power under pulsed conditions are typically about double the voltages required for CW operation [22]. This, and the lower RF power output under CW conditions, are believed to be again an indication of thermally limited conditions, with the contacts contributing significantly to the heat generated in the devices.

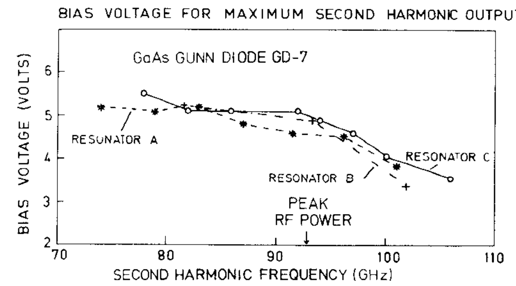

Fig. 19. The required bias voltage for maximum RF power output for resonators with decreasing diameter D (increasing frequency).

XVI. Conclusion

We have presented experimental results on millimeter-wave GaAs Gunn diodes for the disc-post circuit with a post of sufficiently low inductance L_L, such that resonances are possible in the frequency range of 25–60 GHz, which also coincides with the fundamental frequency range of the diodes tested. The diodes had active lengths of 1.8–2.6 μm, and carrier concentrations of $0.8–1.1 \times 10^{16}$ cm^{-3}.

Our measurements have focused on second harmonic Gunn oscillators at 90 GHz using WR-10 waveguide with disc-post resonators at the fundamental frequency of 45 GHz. The diode and its package are an integral part of the fundamental frequency resonator. The disc serves as an efficient impedance-matching network for the second harmonic. The disc diameter should thus be optimized for maximum power output, and the post dimensions varied to achieve operation at the desired frequency. We have indicated which parameters affect the frequency of the fundamental resonance circuit, and at what rate. Because of the limits in the dimensions of the disc, post, and diode in WR-10 waveguide, the useful frequency range of this type of resonator is about 30–60 GHz (60–120 GHz for the second harmonic).

The possibilities of mechanical frequency tuning have been pointed out. Both capacitive and inductive tuning of the fundamental resonator circuit is possible and has been demonstrated. Mechanical capacitors may be replaced by varactors for electronic tuning. Other resonators, such as waveguide, coaxial, quasi-optic, dielectric, or magnetic types, may be used at the fundamental frequency. For extracting the harmonic frequencies, it is necessary to provide efficient coupling at these harmonic frequencies while containing the fundamental within the resonator.

We have shown that erratic oscillator operation occurs when the cutoff frequency of the waveguide is below the fundamental frequency, allowing additional resonances within the waveguide to exist in the fundamental frequency range of the diode. Thus for smooth operation, the waveguide cutoff frequency should be above the fundamental, which is fullfilled with all waveguides for second harmonic operation, but only partially for third harmonic operation. A high-pass filter is required to cut off the fundamental and the second harmonic, if the third harmonic frequency lies above 1.5 times the waveguide cutoff frequency.

Power measurements have been made, and additional measurements are required in order to optimize the radial disc-post circuits discussed for frequency *and* power. This is usually desired in practice.

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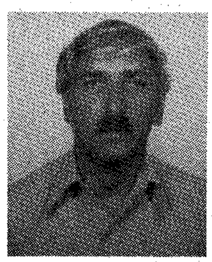

William H. Haydl (M'74–SM'83) received the B.S. degree in electrical engineering from Illinois Institute of Technology, Chicago, IL, in 1962, and the M.S. and PH.D. degrees in electrical engineering from Stanford University, Stanford, CA in 1964 and 1967, respectively.

He was employed as a Research Assistant at the Microwave Laboratory of Stanford University during the years 1962 to 1966, performing research on microwave acoustics, delay lines, acoustic amplification, acoustic instabilities, and oscillations in semiconductors. From 1966 to 1970, he was at the Fairchild Research Laboratory in Palo Alto, CA, and the Science Center of Rockwell International in Thousand Oaks, CA, engaged in work on Gunn-effect devices and gallium arsenide epitaxy. Since 1970, he has been with the Fraunhofer Institute for Applied Solid State Physics (IAF) in Freiburg, West Germany, where he is in charge of the microwave devices group, which is engaged in III–V semiconductor technology, molecular beam epitaxy, and millimeter-wave devices and components.

Dr. Haydl is a member of Tau Beta Pi, Eta Kappa Nu, and Sigma Xi.