A Continuously Tunable 65–115-GHz Gunn Oscillator

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***Abstract*—A phase-locked second harmonic Gunn oscillator, mechanically tunable from 65 to 115 GHz, has been developed for use as a local oscillator (LO) in millimeter radio astronomy. The oscillator's output power is greater than 2 mW over most of its operating range, and exceeds 10 mW from 80 to 102 GHz. Its frequency can be electronically tuned approximately ±200 MHz by varying the bias voltage on the Gunn diode; it is phase locked by exploiting this bias tuning. The oscillator consists of a commercially available, packaged GaAs Gunn diode which is mounted in a coaxial resonator of adjustable length. Descriptions of the mechanical design and phase-lock circuit are given. Extensive experimental measurements of the tuning range and power output for oscillators with different resonator dimensions also are reported.**

I. INTRODUCTION

FOR USE IN millimeter radio astronomy, it is desirable to have a reliable, phase-locked local oscillator (LO) system which may be tuned to any frequency in the 3-mm atmospheric window, from roughly 70 to 115 GHz. Since the cryogenically cooled mixers which are now in use [1] typically require < 0.1 mW of LO power, this system need not have a high power output; even if one allows for 10 dB of loss in coupling the LO into the mixer, a power output of 1 mW is more than adequate. One way to meet these requirements is to use a frequency multiplier to double or triple the output of a lower frequency Gunn oscillator [2]. The multiplier introduces additional complexity into the system, however, and one must still provide a widely tunable oscillator at lower frequencies in order to pump it.

In this paper, a simpler system is described in which the second harmonic output of a 30–60-GHz Gunn oscillator is utilized directly as a frequency source. This approach has a number of advantages. 1) The oscillator is extremely reliable, since it is constructed using a packaged Gunn diode. 2) The oscillator's frequency is insensitive to load mismatches, since its fundamental mode cannot propagate through the output waveguide; thus, a broad-band isolator is unnecessary. 3) The output power is higher than would be produced by a frequency multiplier.

II. PREVIOUS WORK

Numerous designs for second harmonic Gunn oscillators have been described in the literature within the past few years. In all cases, a Gunn diode is embedded in a resonator at the fundamental frequency, and the second harmonic is coupled out through a waveguide which is below cutoff for the fundamental. The resonator may consist of a waveguide cavity [3]–[5] or of a disk and post in a coaxial configuration [6]–[9]. Waveguide cavity resonators normally are tuned with an adjustable backshort; to improve the power output at the second harmonic frequency, a second backshort can be added [4], or the oscillator can be built like a crossed waveguide doubler, with separate waveguides for the fundamental and harmonic [5]. The disk and post resonators are tuned by changing the fringing capacitance of the disk or the inductance of the post. This can be accomplished by inserting a tuning rod near the disk [6], [7], by mechanically changing the length of the post [8], or by changing the resonator position relative to the waveguide [9]. A second harmonic oscillator with a continuous tuning range of 35 GHz (70–105 GHz) and a power output of 6–10 mW has been described [3], and a second harmonic power output of 68 mW at 94 GHz has been reported [9].

The oscillator described here is based on a disk and post resonator with a mechanically adjustable post length—essentially, a variable length coaxial cavity. The frequency tuning characteristics of this design have recently been investigated by Haydl [8]. In this paper, extensive measurements of the power output are reported, as well as the tuning range of oscillators with different resonator dimensions. Through careful optimization of these dimensions, a tuning bandwidth of over 50 GHz has been achieved with a power output of 2 to 20 mW across most of this band. Also, a phase-lock system for the oscillator is described which operates through the diode's bias tuning.

III. BASIC DESIGN

A cross-sectional view of the oscillator is shown in Fig. 1. Half-height WR-10 waveguide (0.63 mm high, 2.54 mm wide) intersects a 2.95-mm-diam coaxial cavity. A packaged Gunn diode is screwed into the waveguide floor, and serves as the bottom wall of the cavity. Bias voltage is supplied to the diode through the cavity's central conductor, a 0.79-mm-diam pin with a thin disk near its end. A bias choke forms the top wall of the cavity. The cavity's length is mechanically adjusted by sliding this choke up and down over the central pin. As shown in Fig. 2, a compression

Manuscript received September 13, 1984; revised February 25, 1985. This work was supported in part by the National Science Foundation under Grant AST 81-14717.

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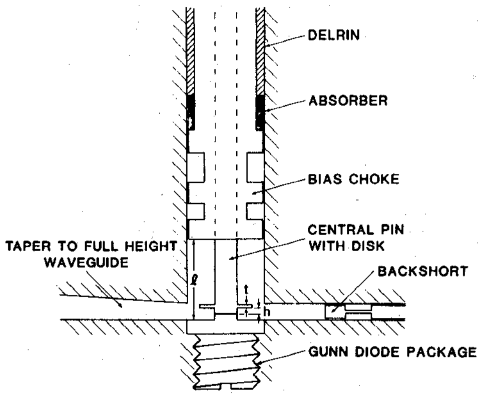


Fig. 1. Cross-sectional view of the coaxial cavity and waveguide. The cavity length is adjusted by sliding the choke up and down over the central pin. A Delrin sleeve insures that the choke will not touch the cavity wall and short out the diode's bias voltage. A ring of absorber attenuates any spurious resonances within the choke assembly. A disk of thickness t is machined as part of the central pin; h is the height of the disk above the top of the diode package. The top of the package is 0.46 mm above the heat sink flange.

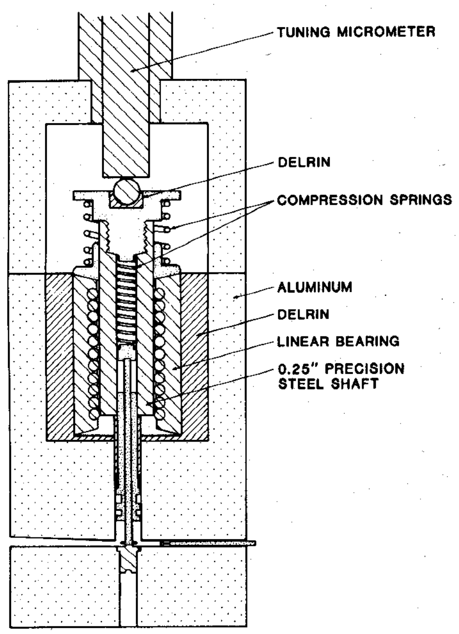
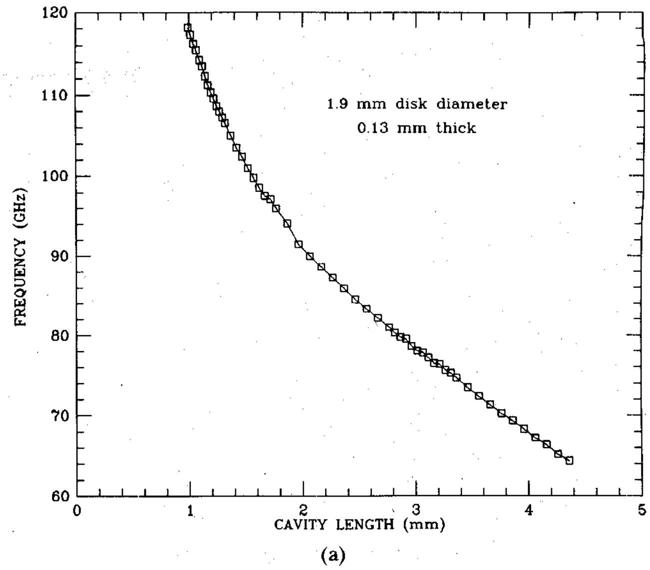
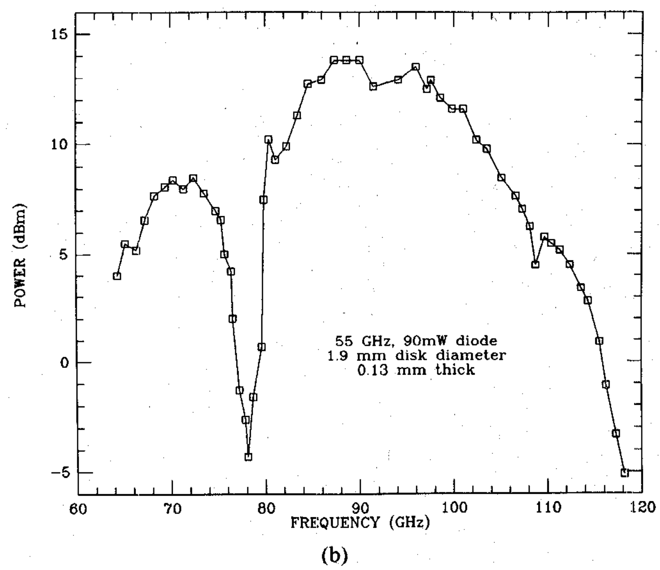


Fig. 2. Cross-sectional view of the entire oscillator showing the mechanical tuning arrangement. The oscillator is approximately 2.8 cm wide. DC bias for the diode is brought in by a flexible wire (not shown) which is attached to the plug threaded into the top of the steel shaft.



(a)



(b)

Fig. 3. (a) Typical tuning curve; output frequency versus cavity length. (b) Output power versus frequency. These data were obtained with a Varian-type VSE-9220S4 GaAs Gunn diode which was rated to have a power output of 90 mW at 55 GHz.

spring inside the choke assembly keeps the pin pressed against the top of the diode package.

The coaxial cavity and Gunn diode form a resonant circuit at the oscillator's fundamental frequency, one half the desired output frequency; by changing the length of the coaxial cavity, one can tune this fundamental frequency from roughly 30 to 60 GHz. The current waveform of the Gunn diode is nonsinusoidal [10], so that higher harmonics of the fundamental frequency also are generated inside the cavity. These harmonics can be coupled out through the WR-10 waveguide. The waveguide's cutoff frequency is 59 GHz, so that the fundamental is completely trapped within the cavity. At the second harmonic frequency, the disk mounted just above the Gunn diode serves as a radial line transformer [11], which matches the low impedance of the diode to the approximately 250-Ω impedance of the reduced height waveguide. A movable backshort in the waveguide behind the cavity also helps to match the second harmonic to the output waveguide.

The frequency tuning range and power output of the oscillator are quite sensitive to the dimensions of the disk, as will be discussed in Section V. A reasonably typical tuning curve, obtained with a disk 1.9 mm in diameter and 0.13 mm thick, is shown in Fig. 3(a). The oscillator's output frequency drops smoothly from 118 to 64 GHz as the length of the cavity (measured from the diode heat sink flange to the bias choke, cf. Fig. 1) is increased from 1.0 to

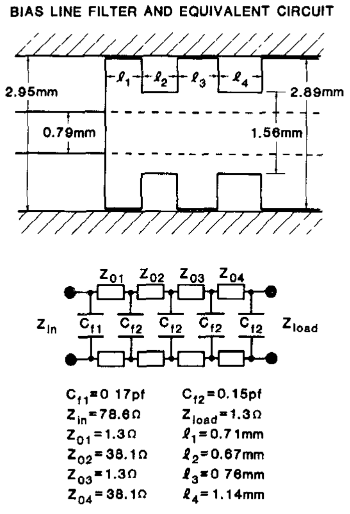


Fig. 4. Bias line filter and equivalent circuit.

4.4 mm. The output power is plotted as a function of frequency in Fig. 3(b). At each frequency, the power was optimized by adjusting the backshort position and the bias voltage. The obvious dip in output power at about 78 GHz is due to an unwanted resonance at this frequency; this dip is discussed more fully in Section VIII. Except in the immediate neighborhood of this dip, the output power exceeds 1 mW over the entire 65–115-GHz frequency range, and is approximately 20 mW from 84–98 GHz.

IV. Bias Choke

The choke used in this oscillator is a four-section noncontacting design which was optimized with the aid of a computer program for circuit analysis (COMPACT, from Comsat General Integrated Systems, Palo Alto, CA). The dimensions of the choke and the equivalent circuit used in the analysis are shown in Fig. 4. The fringing capacitances used in the equivalent circuit were calculated from curves given by Whinnery, Jamieson, and Robbins [12]. Because the transverse dimensions and distances between the discontinuities are not insignificant compared to a wavelength, the capacitances calculated are only rough approximations. The lengths of the four sections were optimized to maximize the amplitude and to minimize the phase-angle variation in the reflection coefficient S_{11} across both the fundamental and harmonic frequency bands (35–55 and 70–120 GHz) simultaneously. The return loss predicted by the program, assuming zero ohmic loss in the choke, was less than 0.01 dB from 30 to 120 GHz; the phase angle was $181 \pm 2°$ across this band. Measurements of the reflection coefficient made on a $10\times$ scale model of the choke agreed closely with the theoretical predictions.

The excellent performance of the choke is due chiefly to the small gap (0.02–0.03 mm) between the first section and the cavity wall. To insure that the choke does not touch the cavity wall and short out the diode bias, the upper section of the choke assembly is encased in a hard plastic (Delrin, manufactured by E. I. du Pont de Nemours, Wilmington, DE) sleeve (cf. Fig. 1). A thin ring of absorbing material (Radite 75, manufactured by LDV Electro Science Industries, Syracuse, NY) is mounted just below this sleeve to attenuate any possible spurious resonances within the choke assembly.

Near the upper end of the oscillator's tuning range, a change of only 0.01 mm in the cavity length produces nearly a 400-MHz change in the output frequency (cf. Fig. 3(a)). Clearly, the mechanism which moves the bias choke up and down must operate very smoothly if the oscillator frequency is to tune smoothly. The tuning mechanism used is illustrated in Fig. 2. The choke is mounted on a 0.25-in-diam precision steel shaft which slides up and down in a linear bearing. To avoid backlash, the shaft is spring-loaded against the tuning micrometer. The entire linear bearing assembly is electrically isolated from the oscillator block with a plastic insert so that a wire carrying the bias voltage for the Gunn diode can be attached directly to this assembly.

Because the oscillation frequency is such a sensitive function of the cavity's length, it is desirable to temperature-stabilize the oscillator block in order to achieve optimum frequency stability. If the oscillator is not adequately heat sunk, frequency drifts of several hundred megahertz can occur after the oscillator is first turned on.

V. Effect of Disk Size on Tuning Range and Power Output

The central conductor of the coaxial cavity consists of a 0.79-mm-diam phosphor bronze pin with a thin disk at one end. The pin is machined to a tolerance of approximately ± 0.005 mm so that it fits snugly into the hole in the center of the choke assembly, yet allows the choke to slide up and down smoothly. The disk is machined as an integral part of the pin. No solder connections are made to the central pin, so that pins with different-sized disks can easily be interchanged.

At the oscillator's fundamental frequency the disk acts as a capacitor, increasing the effective electrical length of the coaxial cavity. Thus, if the cavity's length is held fixed, the oscillation *frequency* depends on the disk's height, diameter, and thickness [8], [13], [14]. At the second harmonic frequency, the disk is roughly $\lambda/4$ in radius, and so serves as a radial line transformer [11]. The effective length of the radial line depends not only on the disk diameter, but also on the fringing capacitance at the edge of the disk, and hence on the disk thickness. The impedance of the radial line, and hence the transformation ratio for the Gunn diode impedance, depends on the height of the disk above the waveguide floor. Thus, the oscillator's output *power* also depends on all of these dimensions.

In order to optimize the disk dimensions, extensive tests were made of the tuning range and power output of the oscillator as the disk diameter, thickness, and height (cf. Fig. 1) were varied. The results of these tests are summarized in Figs. 5–7. Increasing the disk diameter increases the capacitive loading of the cavity, and hence lowers the oscillation frequency (cf. Fig. 5(a)). Increasing the disk diameter also increases the length of the radial

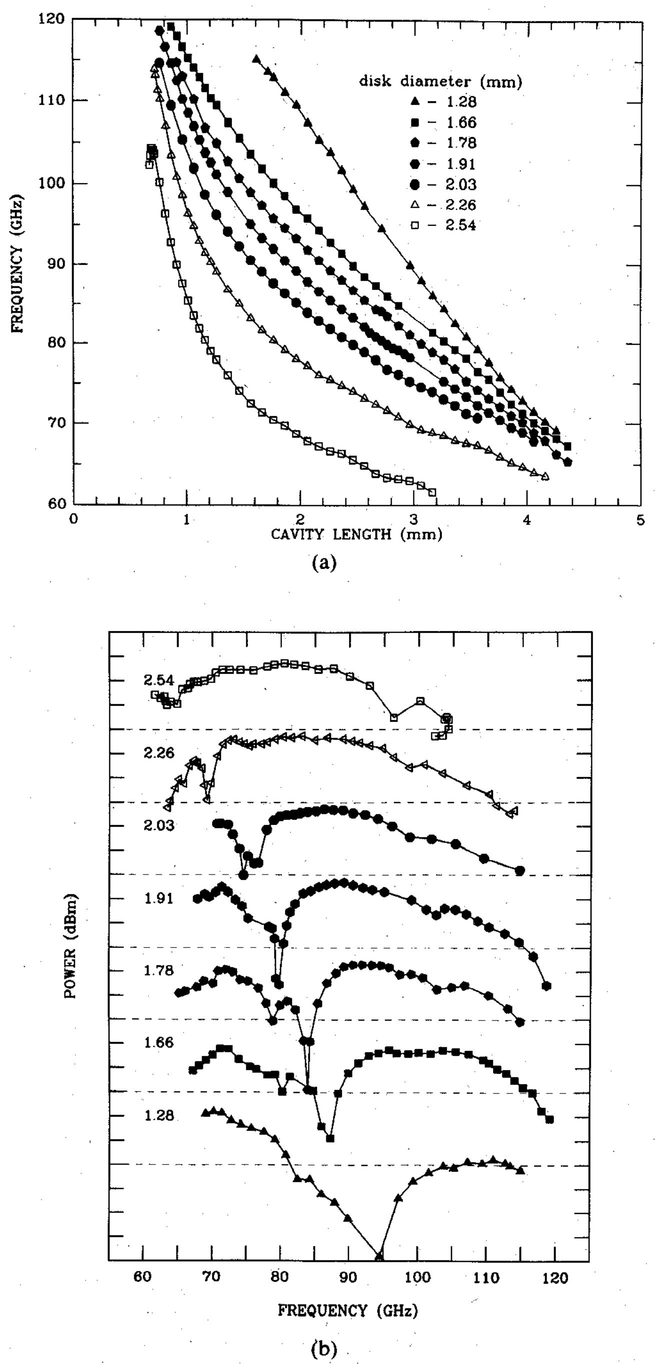


Fig. 5. (a) Tuning curves for one oscillator and diode, and seven disks of different diameters; $t = 0.10$ mm, and $h = 0$ for all disks. The turnover in the curve for the 2.54-mm-diam disk presumably is due to a slow transition in the electric-field configuration from a TEM mode to a radial line mode as the post length is made small. (b) The corresponding output power curves. The dashed line for each curve is at 0 dBm. The tick marks on the vertical axis are at 5-dB increments.

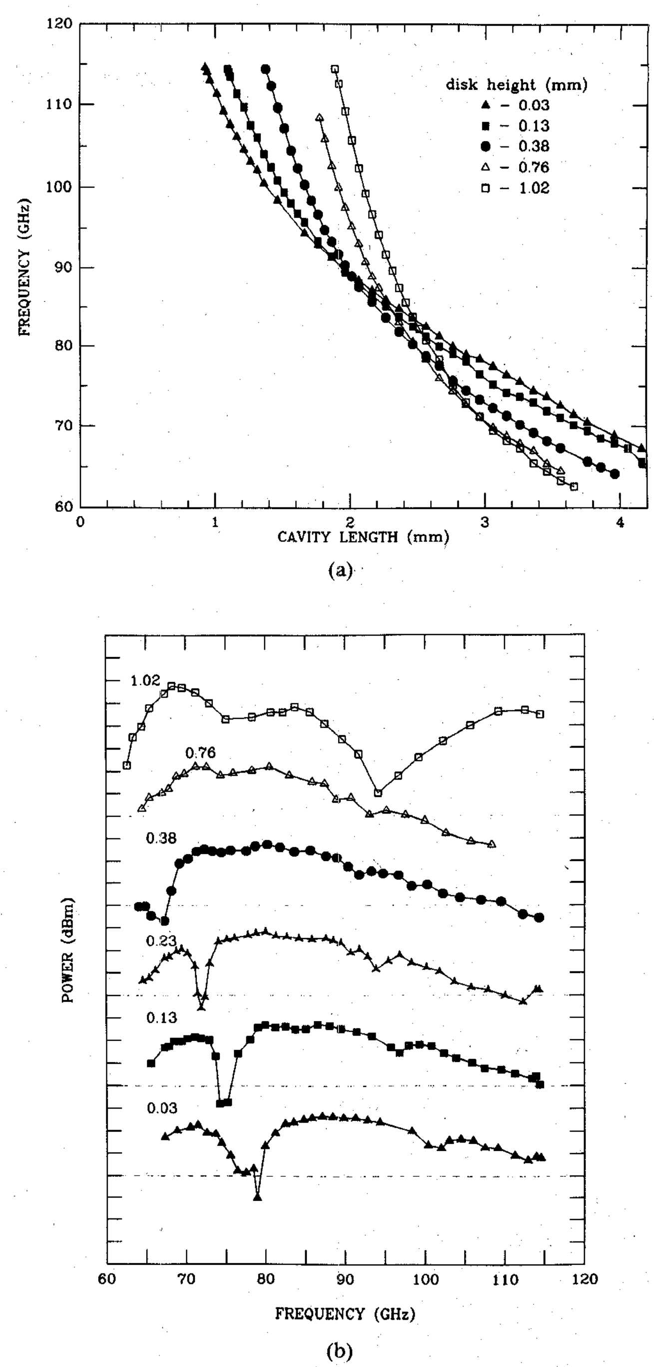


Fig. 6. (a) Tuning curves for five values of the disk height h above the diode package. The data were obtained from the same oscillator and diode. The disk diameter was 1.9 mm; $t = 0.13$ mm. The same central pin was successively shortened between measurements. (b) The corresponding output power curves. The power output curve obtained for a disk height of 0.23 mm is also shown. The dashed line for each curve is at 0 dBm. The tick marks on the power scale are at 5-dB increments.

line, and thus optimizes the power output toward the low end of the frequency band (cf. Fig. 5(b)). The capacitive loading of the coaxial cavity also is increased if the disk is moved into a region of stronger electric field. Thus, increasing the disk's height decreases the oscillation frequency until the disk reaches the midpoint of the cavity; raising the disk further increases the oscillation frequency (cf. Fig. 6(a)). Increasing the disk height decreases the impedance transformation ratio for the second harmonic, and thus lowers the output power, particularly at the high end of the frequency band (cf. Fig. 6(b)). Increasing the thickness of the disk (cf. Fig. 7) mimics both the effects of increased diameter (due to fringing fields) and of increased height. A reasonable compromise for the 70–115-GHz range is a disk diameter of 1.90 mm, a thickness of 0.15 mm, and a height of 0.

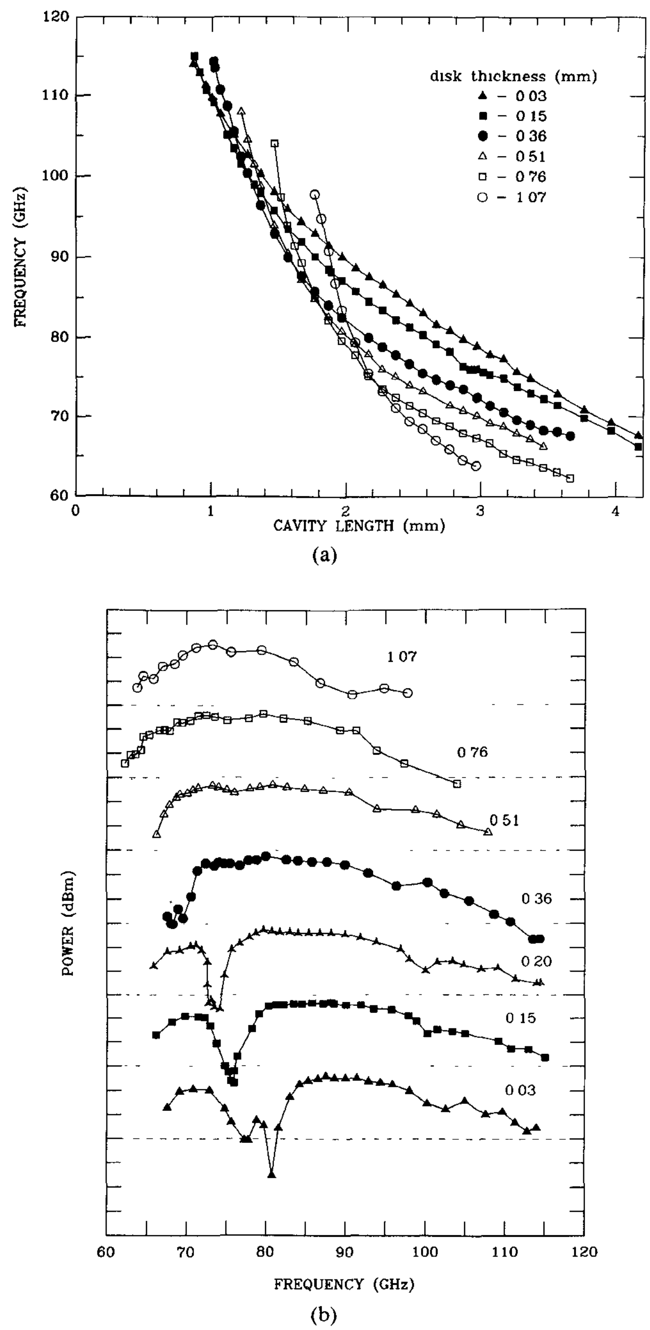


Fig. 7. (a) Tuning curves for six values of the disk thickness t. The data were obtained from the same oscillator and diode. The disk diameter was 1.9 mm; $h = 0$. The same disk was successively machined thinner between measurements. (b) The corresponding output power curves. The power output curve obtained for a disk thickness of 0.20 mm is also shown. The dashed line for each curve is at 0 dBm. The tick marks on the power scale are at 5-dB increments.

Since the fringing capacitance of the disk also depends on the diameter of the coaxial cavity, the optimum disk dimensions will change if the cavity diameter is changed. In the standard design, the cavity is 2.95 mm in diameter, the same diameter as the diode package flange (cf. Fig. 1). Oscillators with cavity diameters of 2.06 mm, 2.39 mm, and 3.94 mm also have been constructed. In the oscillators with smaller cavities, it was necessary to use very small diameter disks in order to tune to 115 GHz, and this cut the power output substantially at the low end of the frequency band. The oscillator with the 3.94-mm-diam cavity exhibited several power dips across the frequency band, possibly because this cavity can support additional waveguide modes at the fundamental frequency.

Oscillators with rectangular "disks" also were tested. The output power varied erratically with frequency, and still exhibited a dip near the low end of the frequency band. Since circular disks are much easier to machine, there seems to be no reason to prefer another geometry.

VI. Gunn Diode

In the course of the development work, 10 different GaAs Gunn diodes were tested. All were manufactured by Varian, and were in the standard N34 package. Typically, these diodes were rated to have power outputs of 70–125 mW at 45 GHz (type VSQ-9219S5), or 70–100 mW at 55 GHz (type VSE-9220S4). One diode (type VSB-9222S2) was rated to have a power output of 18 mW at 94 GHz. Because diodes are simply screwed into the oscillator block, it was easy to test the performance of a number of different diodes in the same block. The oscillator's frequency tuning curve was found to be only weakly dependent on the diode used, but the power output was more variable. In most cases, the oscillator produced 10–20 mW of output power over a bandwidth of approximately 10–20 GHz. However, the center frequency of the peak power band varied by as much as 15 GHz from diode to diode. Presumably this variation is due to differences in the Gunn diode active layer thickness. All diodes tested produced at least 1 mW of power from 80–110 GHz. Diodes which gave the best output power at 115 GHz, as high as 7 dBm, were often unstable below approximately 75 GHz, while diodes which produced substantial power at the low end of the band often gave less than a milliwatt above 110 GHz. Therefore, one may need to specially select a diode to cover the entire 65–115-GHz frequency band with one oscillator.

It was found that the "94-GHz" diode was operating in a 35–58-GHz fundamental mode, since the third harmonic of this mode could be detected in the oscillator's output.

VII. Waveguide Backshort

The waveguide backshort is a two-section noncontacting choke. The backshort position is adjusted only to maximize the power output of the oscillator. If the backshort is kept sufficiently far away from the coaxial cavity (more than about 1 mm), its position has only a minor effect on the oscillation frequency; typically, tuning the backshort over a full guide wavelength pulls the second harmonic frequency less than 50 MHz.

VIII. Power Dip

Figs. 5(b), 6(b), and 7(b) show that there is usually a sharp dip in the oscillator's output power near the low-frequency end of its tuning range; the exact frequency of the dip depends on the dimensions of the disk. The power dip is not due to an unwanted resonance or mode change at the oscillator's fundamental frequency, since as one

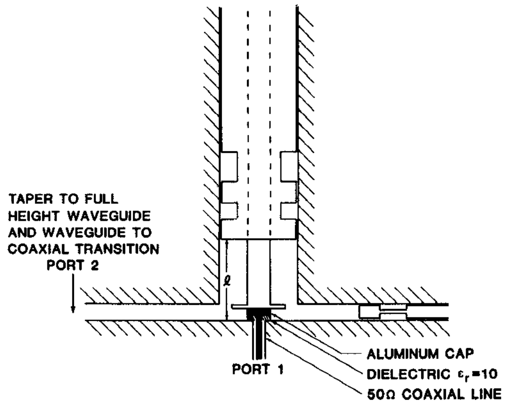


Fig. 8. Cross-sectional view of the model.

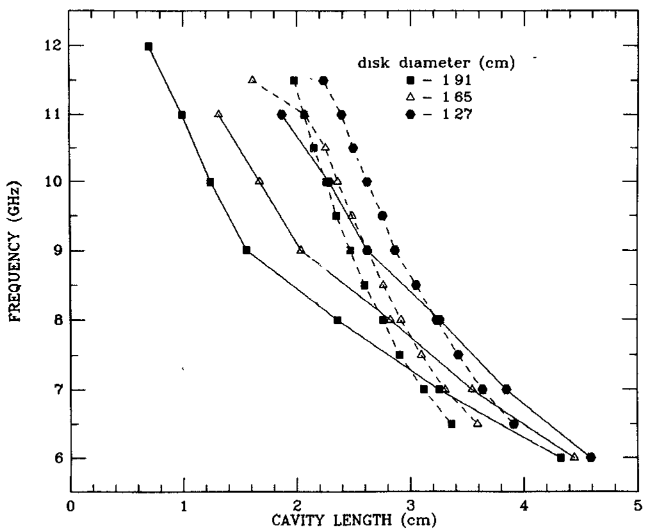


Fig. 9. Tuning curves (solid) and "decoupling" curves (dashed) measured with the model for three different disk diameters; $t = 0.13$ cm, and $h = 0$ for all disks. Frequencies should be multiplied by 10 to compare with the tuning curves of the actual oscillator. Power dips occur where the dotted and solid lines cross.

tunes through the dip 1) the frequency changes continuously, and 2) power at the third harmonic frequency (see Section IX) remains constant. The optimum backshort position changes very rapidly in the neighborhood of the dip, strongly suggesting that the dip is due to an unwanted resonance at the oscillator's second harmonic frequency.

In order to investigate the nature of this resonance, a 10× scale model of the oscillator was constructed (cf. Fig. 8). The diode package was approximated by a cylinder of dielectric ($\epsilon_r = 10$) with an aluminum cap. A 50-Ω coaxial line was introduced through the base of the waveguide, and its central conductor was attached to the cap. A network analyzer was used to measure the fundamental resonant frequency of the cavity (3–6 GHz in the model) as a function of its physical length; at resonance, the effective electrical length equals one-half wavelength. The solid curves in Fig. 9 show twice this resonant frequency (corresponding to the oscillator's second harmonic output) as a function of cavity length, for three different disk diameters. Comparison of these tuning curves with the tuning curves in Fig. 5 shows that the oscillation frequency predicted by

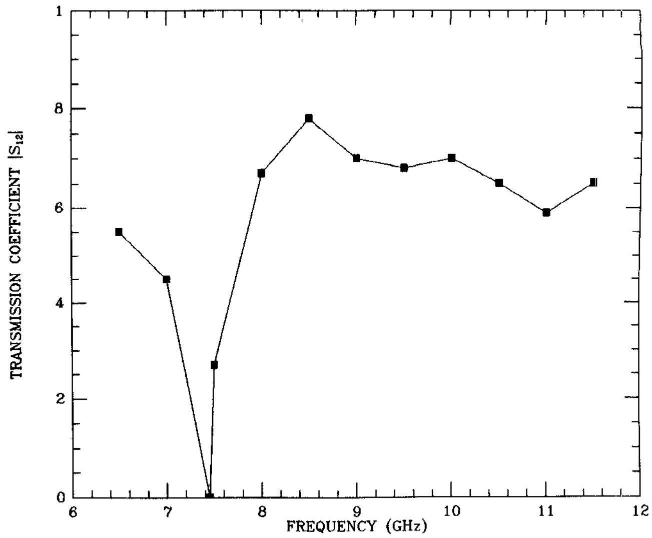


Fig. 10. Model "power" response. For each point, the cavity length was adjusted to be resonant at one half the frequency shown. Note the dip corresponding to the power dip in the actual oscillator. Disk dimensions: diameter = 1.9 cm, $t = 0.13$ cm, and $h = 0$.

the model is about 10 percent too low; this discrepancy is not surprising in view of the crudeness with which the diode was modeled.

At the second harmonic frequency (6.5–12 GHz in the model), the transmission coefficient S_{12}, from the diode port to the output waveguide, was measured as a function of cavity length. The dashed curves in Fig. 9 show the frequencies at which this transmission coefficient was zero. Power incident at the diode port was completely reflected at these frequencies. The backshort position had no effect on S_{11} or S_{12} at these frequencies.

The points where the solid and dotted curves intersect in Fig. 9 should correspond to the frequencies where power dips occur. For these particular lengths, the cavity is resonant at the fundamental frequency, but the second harmonic is decoupled from the waveguide. The model results agree reasonably well with those actually measured. For example, the model predicts that an oscillator with a 1.90-mm-diam disk will have a power dip at 73 GHz, while the actual oscillator has a power dip at 78 GHz (cf. Fig. 3(b)).

The model shows that the power dip is moved toward lower frequencies as the diameter of the disk is made larger. Unfortunately, the curves in Figs. 5(b), 6(b), and 7(b) indicate that the dip cannot be moved completely out of the band of interest without cutting the power output quite dramatically at high frequencies. The model also shows that the tuning and decoupling curves become more nearly parallel as the disk diameter is made smaller; this has the effect of widening the power dip, an effect observed in the data for the actual oscillator (cf. Fig. 5(b)).

The model also made it possible to distinguish whether the rolloff in output power observed at the high end of the frequency band was due to the design of the oscillator or to the diode itself. In Fig. 10, the transmission coefficient S_{12} is plotted as a function of second harmonic frequency; for each point, the cavity length was adjusted to be resonant at

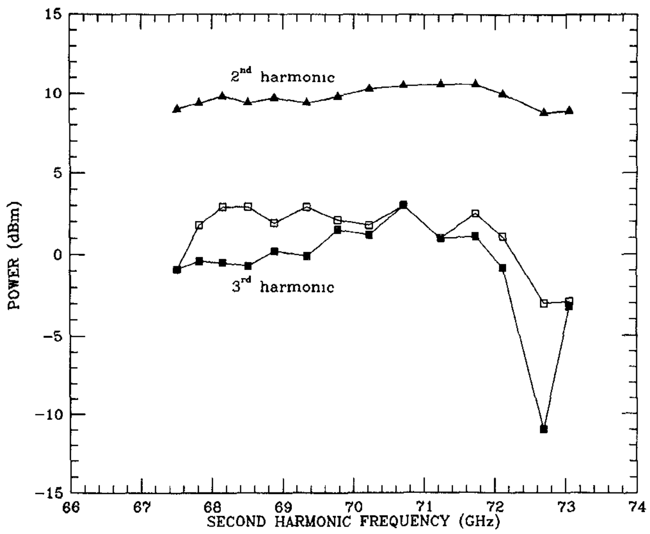


Fig. 11. Third harmonic output power. Open squares: third harmonic power with the backshort position optimized for the third harmonic. Filled squares: third harmonic power with the backshort position optimized for the second harmonic. Filled triangles: second harmonic power.

the corresponding fundamental frequency. From 8 to 11.5 GHz, S_{12} drops by only about 0.5 dB (note that Fig. 11 has a linear scale), whereas from 80 to 115 GHz, the power output of the actual oscillator typically drops by about 10 dB. Therefore, the rolloff in power is attributable to the Gunn diode, not to the coupling efficiency of the oscillator.

It was also observed with the model that the fundamental and harmonic resonances reoccurred when the cavity length was increased by one half a free-space wavelength, confirming that the cavity operates in the TEM mode.

IX. Third Harmonic Output

When the oscillator's output is downconverted to a lower frequency and examined with a spectrum analyzer, the third and higher harmonics appear to be at least 10 dB lower in power than the second harmonic. For second harmonic frequencies above 80 GHz, it is difficult to make more quantitative measurements of the third harmonic power output, since WR-10 waveguide is not single-moded at the third harmonic frequency. However, the third harmonic power was measured when the second harmonic frequency was between 65 and 73 GHz by passing the oscillator's output through a section of WR-8 waveguide (which has a cutoff frequency of 74 GHz). The results of this measurement are shown in Fig. 11. The third harmonic power was measured both with the backshort position optimized for the second harmonic (solid squares) and with the backshort optimized for the third harmonic (open squares). Normally, the third harmonic is about 10 dB lower in power than the second harmonic. At the frequency of the second harmonic power dip, the third harmonic output is not affected and therefore can be comparable in strength.

In the heterodyne receiver in which the oscillator is used, LO power is coupled into the first mixer via a ring filter waveguide diplexer [15]. By choosing the appropriate diplexer mode, the third harmonic can be attenuated by an additional factor of approximately 20 dB. Hence, it is not anticipated that the third harmonic will lead to any calibration difficulties in this application.

X. Electronic Tuning and Phase Lock

The oscillator may be tuned electronically by varying the bias voltage on the Gunn diode. Fig. 12 shows the bias tuning characteristics for an oscillator with a 1.9-mm-diam disk at eight different frequencies within its operating range. A 5.5-V upper limit on the bias was imposed to protect the diode from burnout. If the bias voltage is decreased below the lowest value shown on each plot, the oscillator becomes unstable. Typically, the bias tuning is 600 MHz/V. The total bias tuning range is at least 500 MHz in all cases. Except at 110 GHz, the output power varies by less than 3 dB over this tuning range. At frequencies above about 100 GHz, the bias tuning is not monotonic. The frequency first increases, then decreases, as the bias voltage is increased.

The oscillator is phase locked by means of the bias tuning. A block diagram of the phase-lock circuit is shown in Fig. 13. The oscillator is locked to a frequency $\nu_{osc} = N\nu_X + 80$ MHz, where ν_X is a phase-locked 8–12 GHz reference signal. The search and lock circuit sweeps the bias voltage by approximately ± 0.4 V, corresponding to a frequency sweep of about ± 240 MHz, until the oscillator locks on the upper sideband of the reference signal. The bias voltage is controlled through a power FET. Fig. 14 is a spectrum of the phase-locked oscillator at 100 GHz taken with a spectrum analyzer at the 80-MHz IF. The lock-loop bandwidth is approximately 5 MHz.

In order to minimize the power variations over the phase-lock circuit sweep range, the oscillator should be operated at the voltage V_{pk}, where the power is a maximum. Unfortunately, this is not possible at the high end of the frequency band. Here, the operating voltage V_o must be kept approximately 0.5 V less than the bias tuning "turnaround" voltage V_T so that the phase-lock sweep stays within the monotonic tuning range. At the low end of the frequency band, the operating voltage must be limited to about 5 V so that the phase-lock sweep does not cause the bias voltage to exceed 5.5 V. In Fig. 15, V_{pk}, V_t, and V_o are plotted as a function of frequency for one oscillator. The bias tuning characteristics depend on the disk dimensions, as well as on the diode. For smaller disks, V_t and V_{pk} both increase.

XI. Conclusions

A second harmonic Gunn oscillator has been described which is mechanically tunable over a 50-GHz bandwidth, from approximately 65 to 115 GHz, and which has a power output of 2–20 mW over most of this frequency range. Electronic tuning, via the bias voltage of the diode, has been utilized to phase lock the oscillator. This oscillator is well-suited for use as a local oscillator in millimeter-wave radio astronomy.

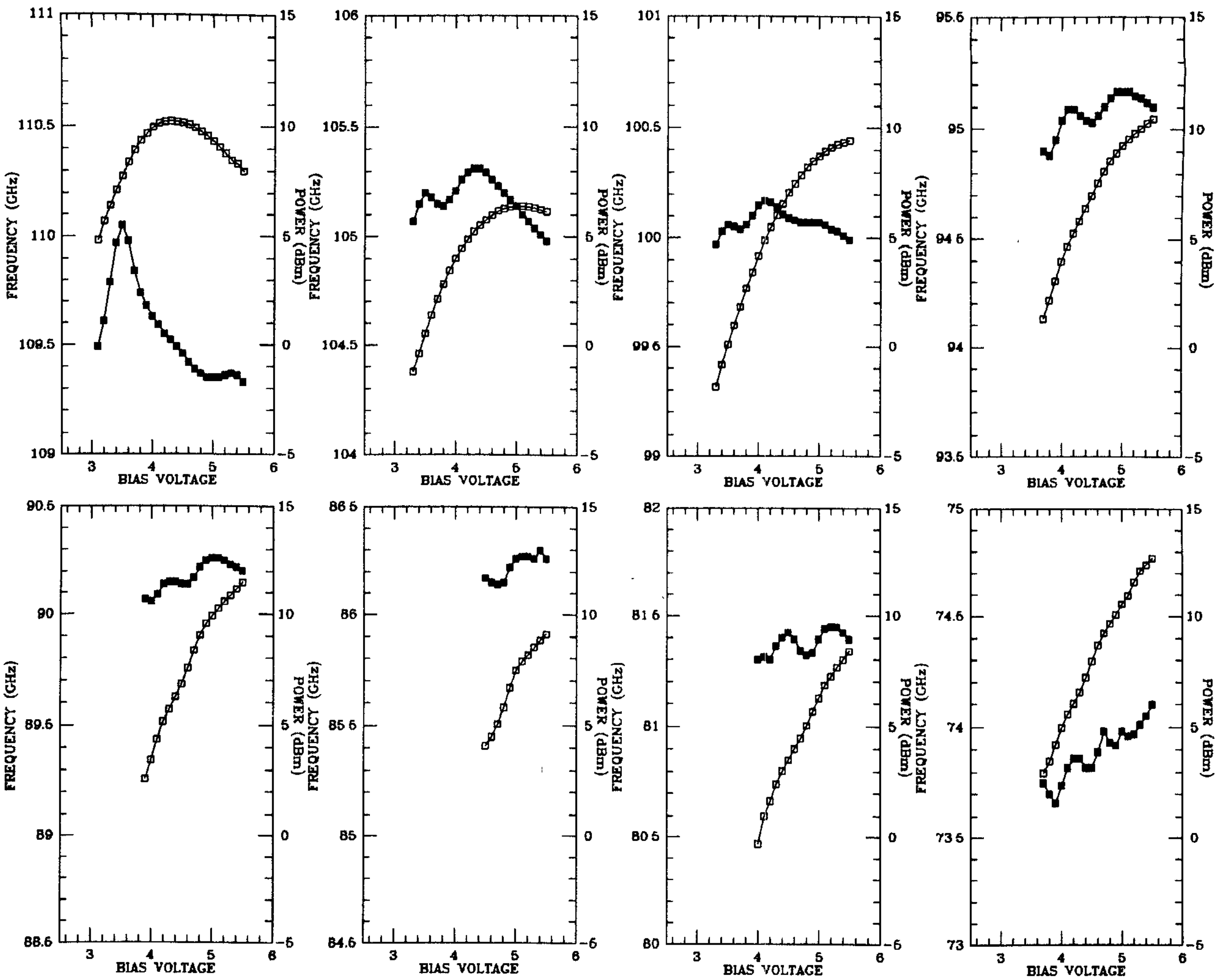


Fig. 12. Bias tuning curves. Frequency (open squares) and output power (filled squares) versus diode bias voltage at eight different frequencies for a typical oscillator. The disk diameter was 1.9 mm, $t = 0.13$ mm, and $h = 0$. The backshort was left in one position as the voltage was changed.

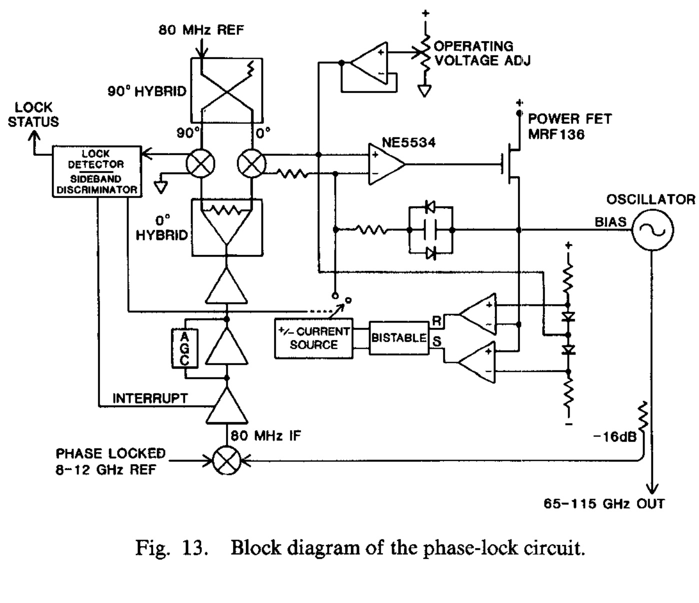


Fig. 13. Block diagram of the phase-lock circuit.

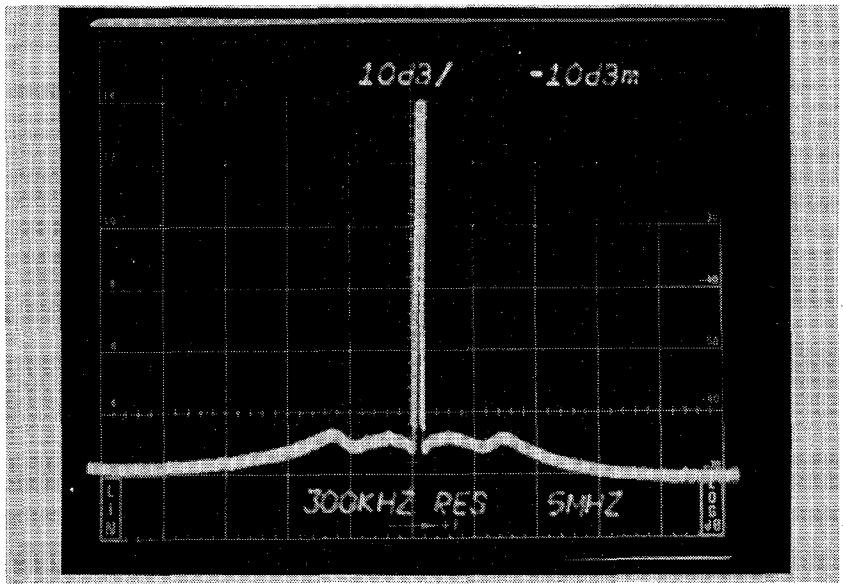


Fig. 14. Spectrum of the phase-locked Gunn oscillator at 100 GHz taken with a spectrum analyzer at the 80-MHz IF. The vertical scale is 10 dB/div and the horizontal scale is 5 MHz/div. The resolution bandwidth is 300 KHz.

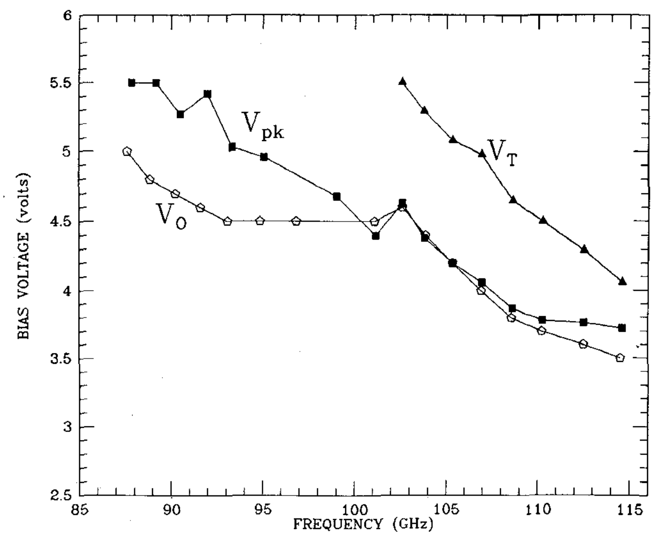


Fig. 15. Operating voltage versus frequency. V_T is the voltage at which the bias tuning curve turns over, V_{pk} is the bias voltage for maximum output power, and V_o is the operating voltage.

The oscillator consists basically of a Gunn diode mounted in a disk and post resonator. The oscillator's tuning range and power output depend sensitively on the dimensions of the disk and, to a lesser extent, on the particular diode used in the oscillator. Power outputs of 10 mW over a 15–30 GHz bandwidth (the center frequency of this band ranged from 80 to 95 GHz) were obtained with most of the diodes tested.

Acknowledgment

The authors would like to thank M. Kopec and C. Peterson of Varian Associates for their help. They also thank A. Räisänen, T. Lum, D. Williams, and J. Welch for useful discussions, and D. Dietrich and L. Amerman for advice on machining techniques.

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