[4] T. Araki and M. Hirayama, "A 20-GHz integrated balanced mixer," *IEEE Trans. Microwave Theory Tech. (Special Issue on Microwave Integrated Circuits)*, vol. MTT-19, pp. 638–643, July 1971.
[5] K. Tomiyasu and J. J. Bolus, "Characteristics of a new serrated choke," *IRE Trans. Microwave Theory Tech.*, vol. MTT-4, pp. 33–36, Jan. 1956.

Oscillation Characteristics of Millimeter-Wave IMPATT Diodes Mounted in Low-Impedance Waveguide Mounts

M. AKAIKE, H. KATO, AND S. YUKI

***Abstract*—Experiments on dc-bias-current-tuned IMPATT diodes mounted in low-impedance waveguide mounts are described. Broad-band bias-current-tuned IMPATT oscillators were obtained which cover almost the full waveguide band; 20-, 24-, and 18-GHz tuning bandwidths were obtained with the R-500, R-620, and R-740 waveguide, respectively. From experiments it became evident that there are some suitable relations for broad-band bias tuning among the diode breakdown voltage, the oscillation frequency, and the waveguide dimension. The results are very useful for the design of the circuit and diode parameter for broad-band millimeter-wave IMPATT sweep oscillators. The feasibility of applying bias-current-tuned IMPATT oscillators to a broad-band measuring instrument is expected.**

I. INTRODUCTION

Many workers have attempted to enlarge the tunable bandwidth of millimeter-wave IMPATT oscillators [1]–[5] in order to apply IMPATT oscillators to the local oscillators in a millimeter-wave transmission system or in order to construct measuring instruments in the millimeter-wave range.

Three schemes for tuning an IMPATT oscillator are possible: 1) mechanical tuning by varying the position of a movable short; 2) tuning by varying the dc bias current of an IMPATT diode; and 3) tuning by varying the reactance or susceptance of the external circuit electrically, for example, by varying the dc bias voltage of a varactor diode located near the IMPATT diode.

The authors previously reported a mechanically tunable IMPATT oscillator in the 50-GHz range, where a 14-GHz tuning bandwidth was obtained by varying the position of a movable waveguide short [2].

The purpose of this paper is to present experimental results on the oscillation characteristics of dc bias-current-tuned IMPATT diodes mounted in low-impedance waveguide mounts (characteristic impedance is about 70 Ω).

The phenomena which have been found in the course of experiments are very useful in designing broad-band IMPATT sweep oscillators.

In Section II, diodes, frequency ranges, and waveguides which were used in the experiments are summarized. The circuit construction of the IMPATT oscillators is described in Section III. In Section IV, the experimental results are presented. The experimental results contain 1) the relation with respect to oscillation frequency, diode breakdown voltage, and the width of the rectangular waveguide in which the IMPATT diode is mounted; 2) oscillation characteristics obtained with various waveguide sizes; and 3) comparison with a mechanically tunable mode of oscillation.

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II. DIODES AND FREQUENCY RANGE

Experiments covered a frequency range of 19–92 GHz with 5 kinds of waveguides (R-220, R-320, R-500, R-620, and R-740), and diodes with 8 different breakdown voltages (V_B = 9.8–38 V). They are listed in Fig. 1 and Table I.

The diodes are of the silicon single-drift-region type. The diode with V_B = 38 V is encapsulated and other diodes are unencapsulated. Fig. 2 shows the structure of an unencapsulated diode.

Diodes with breakdown voltages of 9.8–21 V were fabricated in the Musashino Electrical Communication Laboratory, NTT. Typical oscillation power of a diode with V_B = 13.8 V is about 23 dBm at 80 GHz [6]. In experiments on bias-current-tuned oscillators, this diode was used in the 60-GHz range with an R-620 waveguide. The diode with V_B = 38 V is commercially available as V749 (manufactured by the Nippon Electric Co.) and typical oscillation power is more than 23 dBm at 20 GHz [7].

III. OSCILLATOR MOUNT STRUCTURE

Fig. 3 shows a cross-sectional view of the IMPATT oscillator. The oscillator consists of five parts: an IMPATT diode which is mounted on a copper heat sink, a coaxial line, a rectangular waveguide of

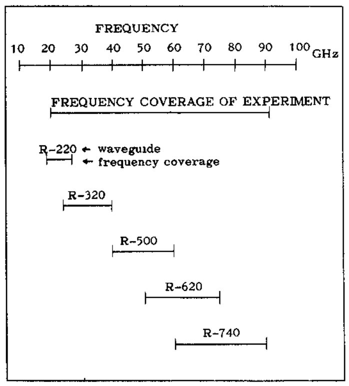

Fig. 1. Waveguide and its frequency coverage. (R-: standardized by the International Electrotechnical Commission.)

TABLE I
DIODE BREAKDOWN VOLTAGE

DIODE #	BREAKDOWN VOLTAGE	NOTE (Maximum oscillation power and its frequency)
# 1	9.8 V	
# 2	10.1 V	
# 3	11.2 V	
# 4	13.8 V	* 82 GHz, 23.3 dBm
# 5	17.2 V	** 42 GHz, 24.1 dBm
# 6	18.6 V	** 40 GHz, 19.7 dBm
# 7	21 V	** 39 GHz, 20.8 dBm
# 8	38 V	*** 20 GHz, 23 dBm

* [6].
** Private letter from Dr. K. Suzuki and Dr. M. Ohmori.
*** [7].

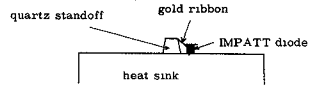

Fig. 2. Structure of an unencapsulated IMPATT diode.

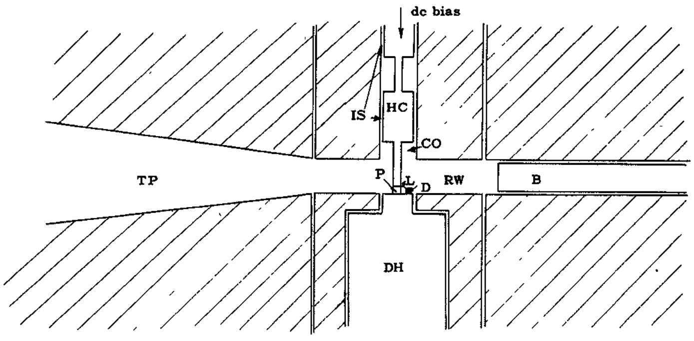

Fig. 3. Structure of a broad-band bias-current-tuned IMPATT oscillator. IMPATT diode: *D*, diode; DH, diode heat sink; *P*, quartz standoff; *L*, gold ribbon. Coaxial line: CO, coaxial line; *CH*, low-pass filter; IS, insulator. RW, reduced-height waveguide. TP, waveguide taper. *B*, movable waveguide short.

reduced height, a waveguide taper, and a movable reduced-height waveguide short.

The coaxial line is cross-coupled to a reduced-height waveguide at the center of the wider wall. The IMPATT diode is put within the rectangular waveguide at the junction of the waveguide and coaxial line. The other end of the coaxial line is terminated by a low-pass filter through which a dc bias is supplied. The width of the reduced-height waveguide is the same as that of the standard waveguide.

The waveguide taper is for impedance matching between the reduced-height and standard waveguides. The VSWR of the taper is designed to be less than 1.1 for the full frequency band of waveguide. The waveguide short, which is a sliding termination of fixed VSWR, levels output power as described in Section IV. The VSWR of this termination is chosen to be between 5 and 10.

The diameter of the coaxial line and the characteristic impedance of the reduced-height waveguide and coaxial line were determined by considering the compromise with respect to the power attenuation factor (oscillation power), parasitic reactances caused by the discontinuity of the junction of the diode and coaxial-line inner conductor, and cutoff attenuation of the higher order mode in a coaxial line. The discussion is presented in the following paragraphs. The oscillators used in the experiments and their inside dimensions are summarized in Table II.

The following discussions are on 60-GHz-band oscillators (R-620 oscillators in Table II). Oscillators of other frequency bands are similarly designed.

The diameter of the coaxial line was determined so as to give a sufficient cutoff attenuation of the higher order mode. The first higher order mode in the coaxial line is the TE_{11} mode. In order to give a TE_{11} cutoff attenuation of above 20 dB/λ_0 (λ_0 is a wavelength) at 150 GHz, which is double the highest frequency of the R-620 waveguide band, the sum of outer-conductor and inner-conductor diameters should be less than 1.2 mm. Moreover, in order to minimize the restrictive effect caused by the parallel capacitance-(which exists at the junction of the IMPATT diode and the inner conductor of the coaxial line) to-oscillator tuning bandwidth, the magnitude of the parallel capacitance should be sufficiently low compared to the junction capacitance of an IMPATT diode. As the junction capacitance of the IMPATT diode is around 0.5 pF (when the junction is at breakdown) for R-620-waveguide-band oscillators, we chose the inner-conductor diameter as 0.3 mm. A diameter of 0.3 mm gives a capacitance less than one-half of the junction capacitance.

The attention factor A [$A = \alpha/(\eta/\sigma\delta)$, α is the attenuation constant of the coaxial line, η is the characteristic admittance of free space, δ is the skin depth, σ is the electrical conductivity of the metal] of a coaxial line at 60 GHz takes the minimum value when the characteristic impedance is around 70 Ω in the case that the diameter of the outer conductor is around 1 mm. The characteristic impedances of the reduced-height waveguide and coaxial line were chosen to be equal in order to maximize the coupling between the waveguide and coaxial line.

TABLE II
OSCILLATOR DIMENSIONS

DIMENSION / OSCILLATOR	DIMENSION OF RECTANGULAR WAVEGUIDE(mm)		DIAMETER OF COAXIAL LINE (mm)		CHARACTERISTIC IMPEDANCE (Ω)
	height	width	outer-conducter	inner-conducter	
R-220 oscillator	0.7	10.668	2.5	0.7	75
R-320 oscillator	0.6	7.112	2.0	0.6	72
R-500 oscillator	0.4	4.775	0.95	0.3	69
R-620 oscillator	0.3	3.759	0.85	0.3	62
R-740 oscillator	0.2	3.099	0.65	0.2	71
MRJ-680 oscillator	0.3	3.43	0.85	0.3	63

IV. EXPERIMENTAL RESULTS

A. Relation Between Oscillation Frequency and Diode Breakdown Voltage

Fig. 4 shows the oscillation frequency (f_o) versus diode breakdown voltage (V_B) obtained by the authors with oscillators listed in Table II. A relation between f_o and V_B exists which is suitable for broad-band dc bias tuning. Table III shows in detail the tuning frequency ranges obtained by the authors. The region surrounded by L_1 and L_2 in Fig. 4 is expressed as

$$2.65 \leq \log_{10} f_o + 0.8 \log_{10} V_B \leq 2.74. \quad (1)$$

Equation (1) shows the relation between f_o and V_B which is suitable for broad-band dc bias tuning in these oscillators.

B. Relation Between Oscillation Frequency and Width of Rectangular Waveguide

When the oscillation frequency becomes higher, frequency jumps or interruptions of oscillation occur due to the generation of higher order waveguide modes around the diode. The magnitude of cutoff attenuation of the TE_{20} mode has a close correlation to the frequency at which these instabilities occur. The lower limit of frequency is determined by the dispersion relation of the TE_{10} mode. Fig. 5 shows the experimental results. In these experiments, the highest

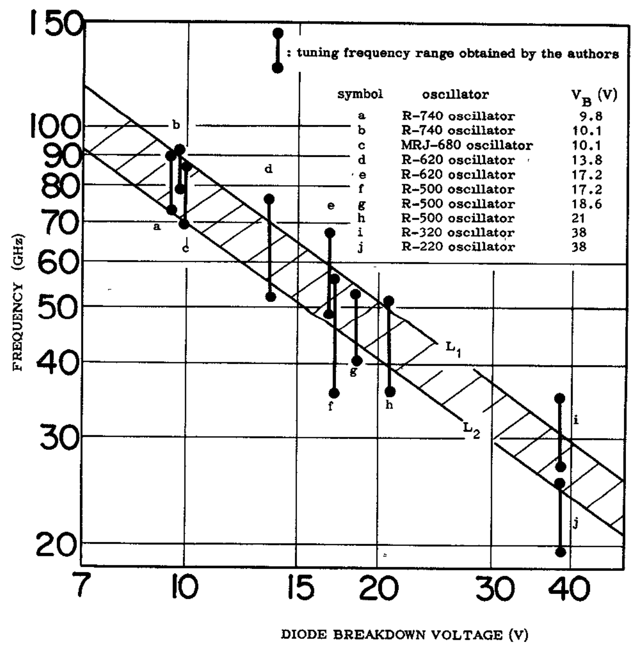

Fig. 4. Tuning frequency ranges obtained by the authors.

TABLE III
TUNING FREQUENCY RANGE OBTAINED WITH BIAS-CURRENT-TUNED IMPATT OSCILLATORS

Symbol in Fig. 7	Frequency Coverage
a	71.5 - 89.5 GHz
b	79.2 - 92.5 GHz
c	69.3 - 85.8 GHz
d	50.9 - 75.0 GHz
e	48.5 - 65.5 GHz
f	34.8 - 55.1 GHz
g	40.5 - 50.4 GHz
h	36.1 - 49.4 GHz
i	26.4 - 34.3 GHz
j	19.0 - 25.7 GHz

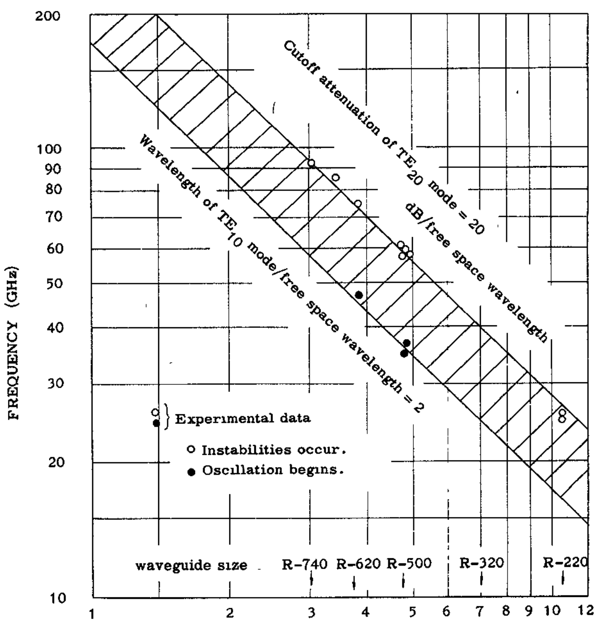

Fig. 5. Oscillation frequency range determined by waveguide dimension.

frequency below which a stable oscillation is obtained is determined by the TE_{20} cutoff attenuation of approximately 20 dB/λ_0, and oscillation begins at the frequency where the ratio of the wavelength of TE_{10} mode to λ_0 is approximately 2. Consequently, the optimum waveguide size depends upon the diode breakdown voltage. Fig. 5 shows that the possible maximum tuning frequency ranges are 36–58, 46–75, and 57–92 GHz for R-500, R-620, and R-740 waveguides, respectively. When the diode breakdown voltage and the waveguide size are optimized, a very wide tuning bandwidth is obtained. The tuning bandwidth covers almost the full waveguide frequency band. These results are useful for the design of the circuit and diode parameters for broad-band millimeter-wave IMPATT sweep oscillators.

C. Typical Tuning Characteristics

Fig. 6 shows the typical tuning characteristics obtained by an R-500 oscillator. Two curves, L_1 and L_2, indicate the results for two different diodes. Diode breakdown voltages, junction diameters, and estimated junction temperatures are shown in the figure. Oscillation begins at about 35 GHz and frequency is tunable up to 55 GHz. Oscillation whose power is less than −20 dBm was detected

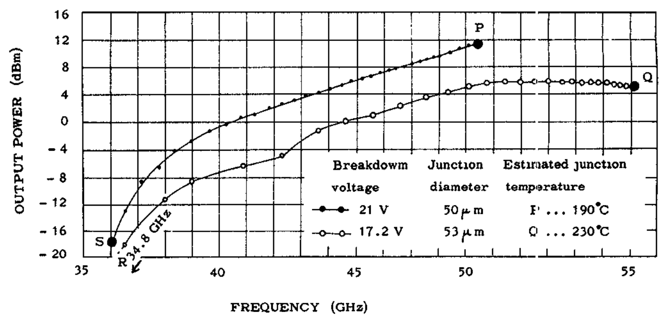

Fig. 6. Typical tuning characteristics of an R-500 oscillator.

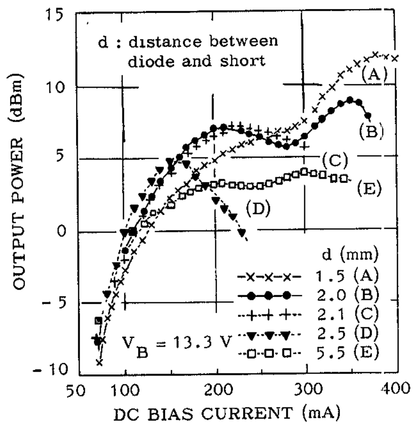

Fig. 7. Typical tuning characteristics of an R-620 oscillator (output power versus bias current). $V_B = 13.3$ V.

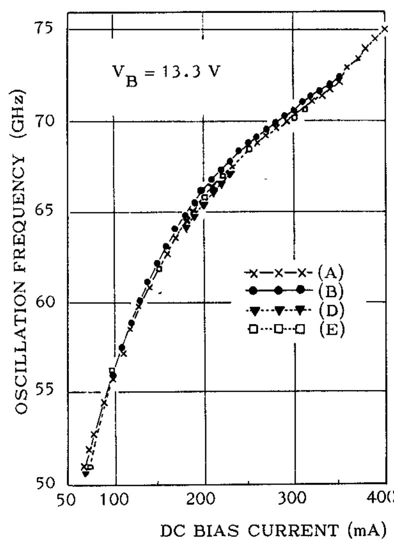

Fig. 8. Typical tuning characteristics of an R-620 oscillator (frequency versus bias current). $V_B = 13.3$ V.

by a crystal detector, and a power of greater than −20 dBm was measured with a power meter. The oscillation still continues beyond the frequencies P and Q in the figure. The dc bias currents are 20 mA, 31 mA, 200 mA, and 300 mA at S, R, P, and Q, respectively.

Figs. 7–9 show the experimental results for an R-620 oscillator. Fig. 7 presents the oscillator power versus dc bias current, and Fig. 8 shows the oscillation frequency versus dc bias current. Tunable frequency range is from 51 to 75 GHz. In Figs. 7 and 8, tuning characteristics are shown for various values of the distance between

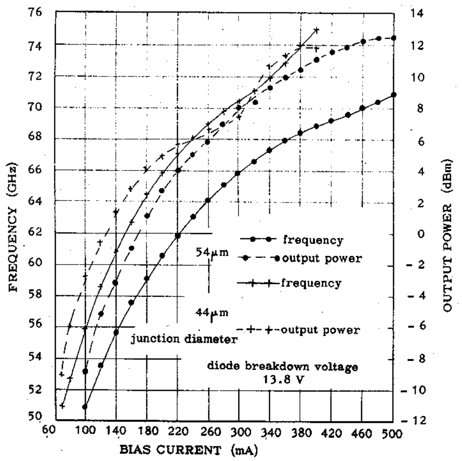

Fig. 9. Typical tuning characteristics of R-620 oscillators for different values of junction diameter.

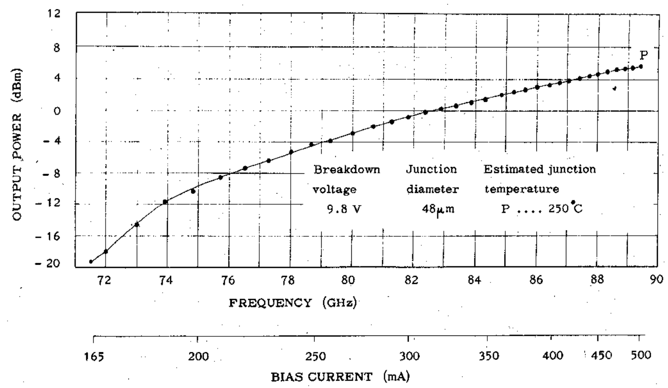

Fig. 10. Typical tuning characteristics of an R-740 oscillator.

diode and waveguide short. The oscillation frequency is not affected by the position of the short (see Fig. 3), while oscillator output power changes by varying the short plunger position. Curve (E) shows that the output power can be leveled by a suitable position of the short for more than 10 GHz. Fig. 9 shows the results for two different values of junction diameter in an R-620 oscillator. Breakdown voltage of the diodes is 13.8 V. When the diameter increases, the oscillation frequency decreases at the same dc bias current. The difference of frequencies of two diode with diameters of 54 and 44 μm is about 6 GHz at a dc bias current of 400 mA. Adjusting the frequency range to some extent is possible by adjusting the junction diameter.

The diodes used in R-620 oscillators are capable of delivering a power of more than 20 dBm at the 40- and 80-GHz bands, as shown in Table I. The maximum oscillator output power of R-620 oscillators is about 10 dBm. In these bias-current-tuned oscillators, the output power is reduced by more than 10 dB. Fig. 10 shows typical results for an R-740 oscillator. Tuning frequency range is from 71.5 to 89.5 GHz. V_B, junction diameter, and estimated junction temperature are shown in the figure.

Fig. 11 shows the typical oscillation spectrum of an R-500 oscillator. Fig. 12 shows the experimental results obtained by an R-500 oscillator, where the VSWR of the waveguide terminator (B in Fig. 3) is chosen so as to give a flat frequency response. The output power variation is less than 2 dB for more than 10 GHz. The VSWR is about 6 in this case.

In these experiments isolators are inserted between the IMPATT oscillator and the load to prevent instabilities in oscillation due to RF reflection from the load. It was found through experiments that a 35-dB isolation was necessary when the load impedance was 0 or ∞. The isolator is of the self-resonant type, and it covers the full frequency band of a waveguide with an isolation of 20 dB, insertion loss of less than 2 dB, and VSWR of less than 1.1 [9].

D. Comparison with Other Modes of Oscillation

Figs. 13–15 show the results obtained by an R-500 oscillator, in which the diode breakdown voltage and oscillation frequency range do not satisfy (1). Diode breakdown voltage is 11.2 V. Fig. 13 presents the output power and frequency as a function of the distance between diode and short. Distance is normalized by λ_g (λ_g is the wavelength in the waveguide). It shows that the distance is about 0.4 λ_g or 0.8 λ_g at any frequency of oscillation. Fig. 14 shows typical bias-tuning characteristics. Fig. 15 presents the results obtained by a circuit which is adjusted so as to give the maximum bias-tuning bandwidth. Jumps of oscillation occur as shown in Figs. 14 and 15. The bandwidth tunable with a short plunger is about 7 GHz, it is about three times the bandwidth tunable by bias current. In such oscillators, as shown in Figs. 13–15, frequency is more readily tunable by a short plunger than by bias current.

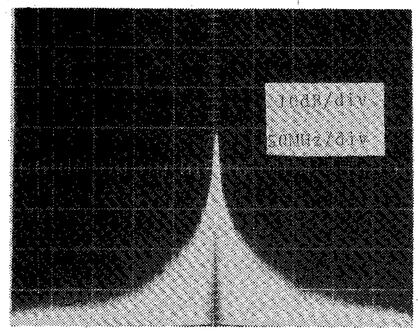

Fig. 11. Typical oscillation spectrum of an R-500 oscillator. Frequency = 47 GHz.

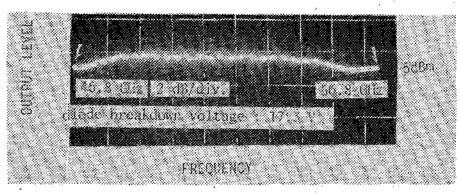

Fig. 12. Output power leveled by a short plunger (an R-500 oscillator).

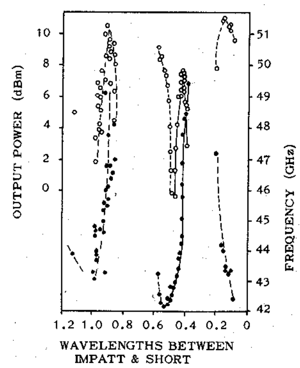

Fig. 13. Typical oscillation characteristics of an R-500 oscillator with a 11.2-V diode (output power and frequency as a function of distance between diode and short). ● Frequency. ○ Output power.

Also, in the case of the oscillator that was previously reported by the authors as a broad-band mechanically tunable oscillator [2], it was found experimentally that the maximum tunable bandwidth by dc-bias-current tuning was less than 3 GHz.

Fig. 16 shows the typical oscillation spectrum of the present mechanically tunable oscillators [8].

Oscillators of this kind were not suitable for broad-band bias-current tuning in our experiments.

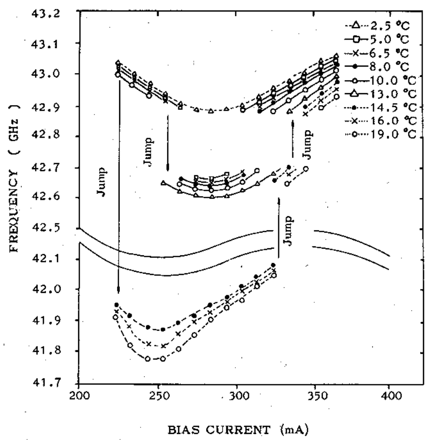

Fig. 14. Typical bias-tuning characteristics of an R-500 oscillator with a 11.2-V diode (parameter: oscillator temperature).

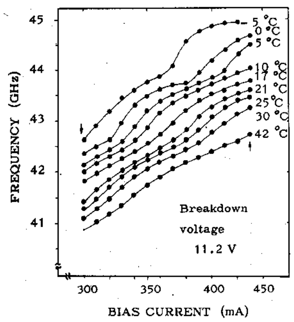

Fig. 15. Frequency as a function of bias current for an R-500 oscillator with a 11.2-V diode. ⬆ ⬇ Frequency jumps occur.

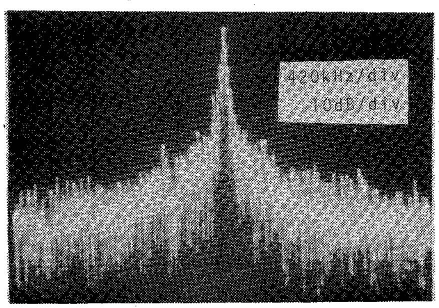

Fig. 16. Typical oscillation spectrum of a mechanically tunable oscillator. Frequency = 47 GHz.

V. CONCLUSION

The authors investigated experimentally the oscillation characteristics of IMPATT diodes mounted in low-impedance waveguide mounts for a frequency range of 19–92 GHz. Broad-band bias-current-tuned oscillators were obtained which cover almost the full waveguide bands; 20-, 24-, and 18-GHz tuning bandwidths were obtained with the R-500, R-620, and R-740 oscillators, respectively.

With respect to our broad-band bias-current-tuned IMPATT oscillators, the following points became evident from the experiments.

1) Oscillation frequency (f_o) and diode breakdown voltage (V_B), which are suitable for broad-band bias-current tuning, satisfy the following relation:

$$2.65 \leq \log_{10} f_o + 0.8 \log_{10} V_B \leq 2.74. \tag{2}$$

In this case, however, oscillator output power is reduced by more than 10 dB, compared to the oscillator operating in the frequency range in which the maximum power is obtainable. The oscillator which does not satisfy the relation in (2) had a fairly broad bandwidth by mechanical tuning, but had only a narrow bias-tuned bandwidth.

2) For the circuit limitation to the oscillation frequency range, the upper and lower limits of oscillation frequency are determined by the cutoff attenuation of the higher order mode (TE_{20}) in the rectangular waveguide and the ratio of the TE_{10} wavelength to the free-space wavelength, respectively. In the present case, the cutoff attenuation was about 20 dB/λ_0 and the ratio was approximately 2.

3) In these oscillators, the output power changes with the change in the impedance of the short plunger, while the change in the oscillation frequency is quite small. Therefore, the output power could be leveled by choosing a suitable value of the short-plunger impedance.

These results are useful for designing a bias-current-tuned broad-band IMPATT sweeper. The authors have built an experimental setup of a sweep oscillator.

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REFERENCES

[1] T. P. Lee and R. D. Standley, "Frequency modulation of a millimeter-wave IMPATT diode oscillator and related harmonic generation effects," *Bell Syst. Tech. J.*, vol. 48, pp. 143–161, Jan. 1969.

[2] Y. Fukatsu, M. Akaike, and H. Kato, "Amplification of high-speed PCM phase-shift-keyed millimeter-wave signals through an injection-locked IMPATT oscillator," in *ISSCC Dig. Tech. Papers*, Feb. 1971, pp. 172–173.

[3] T. A. Midford, H. J. Kuno, and J. W. Tully, "New solid state components for millimeter wave system," *Microwave J.*, vol. 71, pp. 34–42, Nov. 1971.

[4] S. Yuki and M. Akaike, "A bias current tuned millimeter-wave IMPATT oscillator," Inst. Electron. Commun. Eng. Jap., Rep. Tech. Group on Microwaves, 1972, pp. MW 72–112.

[5] H. Kondo and S. Nagano, "A 50-GHz band IMPATT sweep generator," presented at the Nat. Conv. Inst. Electron. Commun. Eng. Jap., Apr. 1972, Paper 854.

[6] M. Ohmori, M. Ino, and T. Makimura, "Performance of 80 GHz band silicon IMPATT diodes with abrupt junctions," *Trans. Inst. Electron. Commun. Eng. Jap.*, vol. 55-C, pp. 678–679, Nov. 1972.

[7] M. Isugi, I. Haga, and H. Nagao, "IMPATT oscillators using V749," presented at the Conv. Inst. Electron. Commun. Eng. Jap., Apr. 1971, Paper 605.

[8] M. Akaike, Y. Fukatsu, and H. Kato, "A millimeter-wave IMPATT local oscillator and its noise performances," *Trans. Inst. Electron. Commun. Eng. Jap.*, vol. 56-B, pp. 169–175, May 1973.

[9] S. Shibata, T. Suzuki, and T. Ohhara, "Millimeterwave isolator," Inst. Electron. Commun. Eng. Jap., Rep. Tech. Group on Component Parts and Materials, Dec. 1973, CPM 73-93.

A Stabilized MIC Oscillator Using a Germanium Avalanche Diode

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***Abstract*—A stabilized X-band oscillator using a germanium avalanche diode in a microwave integrated circuit (MIC) is proposed. The stabilization is achieved by coupling a transmission cavity to the resonant cavity in which an avalanche diode is embedded. A mode-jumping problem inherent in a coupled-cavity oscillator was solved by coupling a third varactor-embedded low-Q cavity to the transmission cavity. As a result, single-mode oscillation in an MIC oscil-**

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