possible explanation is that, as the varactor enters breakdown, an ionization-mode space charge is set up which introduces a reactance into the circuit, thereby altering frequency with time, depending on the temperature coefficient of the reactance. Third, the varactor Q may be reduced when drawing reverse current. Possibly all three are responsible. In this connection it is possible that reduction in varactor Q could be responsible for the degradation in PTD measured when the varactor draws forward current. In the forward-conduction region the varactor Q does drop significantly due to both increased capacitance and increased series resistance.

In a similar manner, the effect of changes in dissipated power in the TED may be studied. The changes in dissipated power are due to two factors. First, the negative conductance changes with frequency, and second, the dynamic operating point of the TED changes due to changes in saturation level and hence small changes in rectified dc current. The total magnitude of these power changes is uncertain, but for purposes of estimation will be taken to be on the order of 20 mW.

In this case, the thermal resistance of the mounted TED chip is much smaller since it is mounted "flip chip," i.e., the active portion of the semiconductor is mounted closest to the package pedestal. For the TED used, the chip-to-pedestal thermal resistance is $R_c = 15°C/W$ and hence the temperature rise is much smaller than the varactor; i.e., $\Delta T = 0.3°C$. However, the temperature coefficient of the frequency shift at resonance is larger. This has been measured to be $C_{TF} = 0.086$ percent/°C, corresponding to a frequency shift of 2.7 MHz at 10 GHz. To calculate the time constant, the mass times the specific heat ($C_V = 0.086$ cal/g · °C) gives the thermal capacitance $C_C = 21.8 \times 10 \times 10^{-6}$ W · s/°C; then $\tau = R_c C_c = 327$ μs. Thus the thermal effects of the TED are expected to be significant from 10 μs to 1 ms. This probably is important at time periods somewhat less than 10 μs, since the thermal resistances and capacitances are actually composites of the three regions that make up the TED chip, along with the interfaces of the metal semiconductor ohmic contacts. These regions and their interfaces have differing thermal resistances and capacitances due to their differing doping levels. This would also apply to the varactor-tuning diodes. It is seen that time periods of thermal drift for the two semiconductor devices overlap somewhat, which makes isolation of these effects difficult. Measurements on a number of VCO's indicate that these thermal effects are settled out by about 50 ms.

For the time period prior to a few microseconds, effects other than thermal may be responsible for frequency drifts. This requires further study.

Conclusion

The experimental study has shown that if the previously discussed techniques are employed, the PTD of an X-band TED VCO can be significantly reduced for the time period from 1 μs to 100 ms. To do this, the oscillator power and the output power must be kept low and the bandwidth restricted to prevent the varactor from drawing large forward or reverse current. Finally, a high-Q varactor-tuning diode must be used.

References

[1] D. Large, "Octave band varactor-tuned GUNN diode sources," *Microwave Journal*, vol. 13, pp. 49–51, Oct. 1970.
[2] K. M. Johnson, "Widebandwidth IMPATT and GUNN voltage tuned oscillator," in *1972 IEEE-GMTT International Microwave Symposium Digest of Tech. Papers*, pp. 185–186, May 1972.

Absolute Load Detection with Microwave Gunn Oscillators

LARRY D. PARTAIN, MEMBER, IEEE, W. ALLAN COOK, HUA-FENG HUANG, MEMBER, IEEE, AND LEWIS C. GOODRICH, MEMBER, IEEE

Abstract—**The change in the dc I–V properties of Gunn-flange microwave oscillators with a change in microwave load are shown to provide a method of measuring the physical properties of dielectric samples that only requires the measurement of dc voltages and currents. A phenomenological equivalent-circuit model has been developed that predicts a dependence of detection sensitivity on bias resistance that agrees closely with experiment and that explains the restrictions on such a bias resistor's maximum allowed value. Properties of a prototype system capable of measuring sample size with 8-percent accuracy are presented.**

I. Introduction

It is well known that microwave oscillators are quite sensitive to the load impedance they see. A high degree of isolation between a source and a variable load is usually necessary to achieve stable operation. However, if close coupling is used, oscillator power and frequency variations with load changes can be used to measure load properties. Such measurements can be accomplished rapidly, continuously, and with no mechanical contact with the load.

The strong dependence of Gunn microwave oscillators on load has been studied [1] as a means of tuning and of obtaining maximum output power. Utilizing this effect, Nagano and Akaiwa [2] have described a method for measuring the relative velocity of a moving-target load by monitoring oscillatory changes in the dc bias current flowing through a Gunn device. Application of their results leads to extremely simple Doppler radar systems. Generalized treatments have been presented by Takayama [3] and by Nygren and Sjolund [4] for such Doppler-signal detection with various negative-resistance-device oscillators such as Gunn oscillators.

In this short paper we discuss extensions of these earlier results that allow absolute values of load parameters to be measured by monitoring just the dc voltage and current of Gunn-device oscillators. In Section II we describe the measurement apparatus and the experimental results. In Section III a phenomenological equivalent-circuit model is developed that predicts a given dependence of detection sensitivity on dc bias resistance that is verified by experiment.

II. Experimental Results

The dc current-voltage measurements were made using two $4\frac{1}{2}$-digit digital multimeters and a variable-voltage power supply. The Gunn devices were mounted in X-band Gunn flanges whose construction and operating characteristics have been described elsewhere [5]–[7]. The dc properties of these flanges are to serve as low-pass filters so that no microwave or high-frequency signals generated by the Gunn device reach the flange terminals. In order to demonstrate that the experiments were characteristic of a range of systems, measurements were taken on two different flanges attached to one of three different cavities. One flange was a Frequency West G0(X)-104 flange with the Gunn device permanently mounted. The other was a Frequency West G0(X)-107 flange slightly modified to accept a Microwave Associates

Manuscript received May 27, 1975; revised March 5, 1976.
L. D. Partain is with the Department of Electrical Engineering, University of Delaware, Newark, DE 19711.
W. A. Cook, H. F. Huang, and L. C. Goodrich are with the Engineering Physics Laboratory, E. I. DuPont Company, Wilmington, DE 19898.

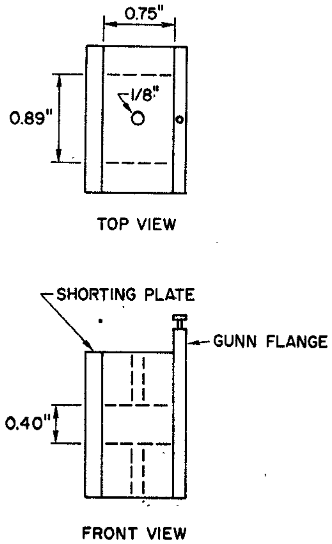

Fig. 1. The 0.75-in-long rectangular microwave cavity.

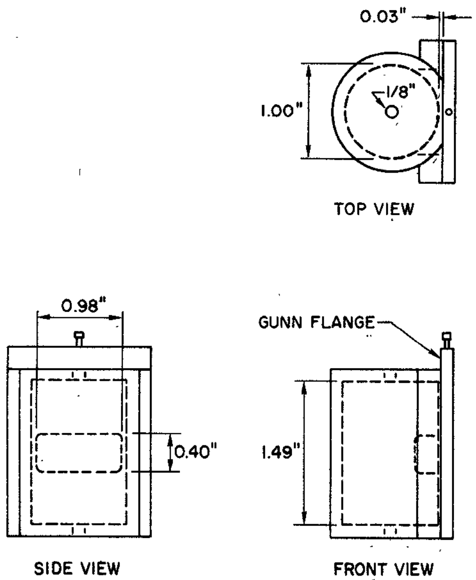

Fig. 2. The cylindrical microwave cavity.

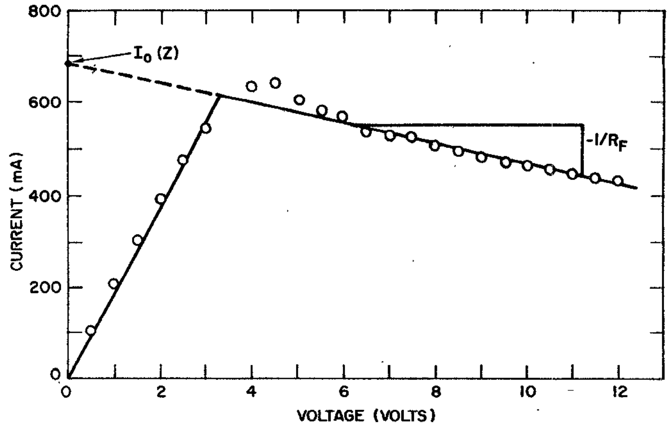

Fig. 3. *I–V* characteristics of the G0(X)-104 Gunn flange attached to the cylindrical cavity. The data points were experimentally measured. The solid lines are the two-segment, piecewise linear approximation to this *I–V* characteristic.

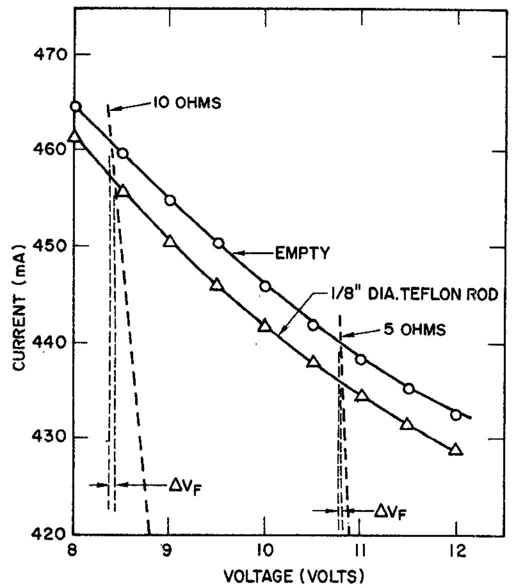

Fig. 4. Shift in the *I–V* characteristics above threshold for the modified G0(X)-107 Gunn flange attached to the 0.75-in-long rectangular cavity when a Teflon® rod is inserted into the cavity. The data were obtained for decreasing voltage. The dashed lines are the load lines for 5- and 10-Ω bias resistors and a 13-V supply.

MA 49158 Gunn device in place of its permanently mounted device. These flanges were clamped to either the 0.75-in-long rectangular cavity or the cylindrical cavity as shown in Figs. 1 and 2. The third type of cavity was identical to that shown in Fig. 1 except that it was 1 in long. The cavities were constructed of gold-plated brass. These oscillators were then connected to an approximately 4-ft-long section of *X*-band waveguide terminated by a matched load. Tapped off of this 4-ft section were three directional couplers. A 10-dB coupler connected to a Hewlett-Packard Model 431B Power Meter, a 20-dB coupler was attached to an EIP Model 350D Microwave Frequency Counter, and the third 10-dB coupler was attached to a Vectron Model SA30 Microwave Spectrum Analyzer.

The dc *I–V* characteristics of the G0(X)-104 Gunn flange attached to the cylindrical cavity is shown in Fig. 3. No detectable microwave power was obtained until the flange voltage reached 8 V. As the voltage was raised from 8 to 12 V, the oscillator power increased monotonically from 9 to 31 mW and the frequency decreased monotonically from 8.819 to 8.812 GHz. The mode structure for such 8.8-GHz oscillations was identified as TM_{010} from a cylindrical-cavity mode chart [8]. These are typical operating characteristics of a Gunn-device oscillator [9]. Similar results were obtained with the rectangular cavities.

When cylindrical dielectric samples were inserted through the $\frac{1}{8}$-in hole of the cavities attached to a flange, shifts occurred in the active region of the dc *I–V* characteristics of the flanges. A typical shift is shown in Fig. 4, which shows the effect of inserting a $\frac{1}{8}$-in-diam Teflon® rod into the 0.75-in rectangular cavity fastened to the modified G0(X)-107 flange. This shows that the presence of this rod could be detected just by monitoring the shift in the dc current flowing through the Gunn flange. Similar shifts occurred when nylon and Teflon® samples were introduced into the cylindrical-cavity oscillator and the other rectangular-cavity oscillator. The only significant difference was that the current level was found to increase with sample insertion for the cylindrical system (see Fig. 7) in contrast to the decrease

® Registered trademark of E. I. DuPont Company, Wilmington, DE.

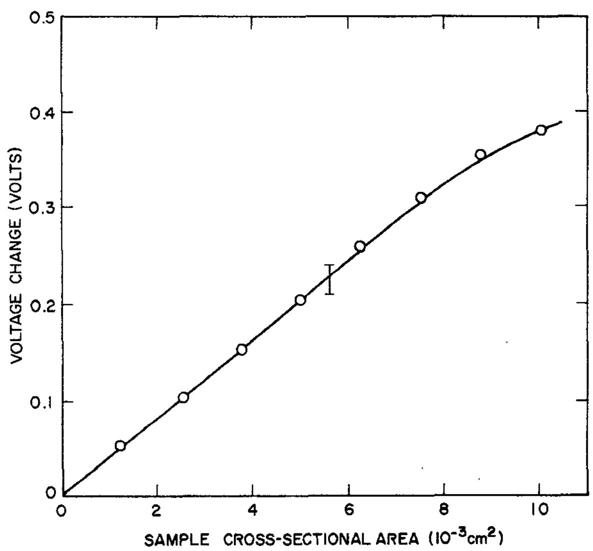

Fig. 5. Change in the voltage of the G0(X)-104 flange attached to the 1-in-long rectangular cavity as a function of the cross-sectional area of nylon samples. A 10-Ω bias resistor and a 15-V supply were used. Error bar indicates uncertainty due to hysteresis.

observed for the rectangular ones as shown in Fig. 4. Analogous shifts in the I–V characteristics of a Baritt diode with changes in the microwave load were described by Nygren and Sjolund [4].

The current changes induced by sample insertion can be converted into voltage changes by connecting a bias resistance in series with the Gunn-flange oscillator and a constant voltage supply. An exact solution for such voltage changes with nonlinear-device characteristics is obtained by using the standard dc load-line analysis [10]. The two dashed lines in Fig. 4 are the load lines for 5- and 10-Ω bias resistors and a 13-V power supply. The intersection of these load lines with the flange-oscillator I–V characteristics specify the flange operating voltage and the change is this voltage ΔV_F. As shown, the larger bias resistance gives a larger voltage change. The magnitude of this change is modeled more specifically in Section III. Similar bias-resistor load lines were plotted by Nygren and Sjolund [4] on their Baritt-diode I–V curves.

A simple system for measuring sample parameters is obtained by utilizing this bias-resistor circuit and by monitoring the flange-oscillator voltage. Fig. 5 shows how this voltage change varies with the cross-sectional area of nylon test samples using the G0(X)-104 Gunn flange attached to the 1-in-long rectangular cavity. A 10-Ω bias resistor and a 15-V supply were used for this measurement. In this manner the size of samples of known dielectric constant are determined by the near-linear change in the measured dc voltage with sample area. Similar variations in voltage change were obtained when either sample temperature or moisture content was varied. This demonstrated the capability to monitor more than one type of physical-parameter variation.

The accuracy of such measurements is limited by the hysteresis error occurring with these Gunn-flange oscillators. If a sample parameter-like cross-sectional area is cycled, the dc voltage level of the device oscillator does not return precisely to its original value. The uncertainty resulting from this hysteresis is indicated by the error bar in Fig. 5. This limited the measurement accuracy to approximately 8 percent for this configuration.

III. Phenomenological Model

A model for this bias-resistor detection process may be obtained by using a piecewise linear approximation of the I–V characteristics of the Gunn-flange oscillator as shown in Fig. 3.

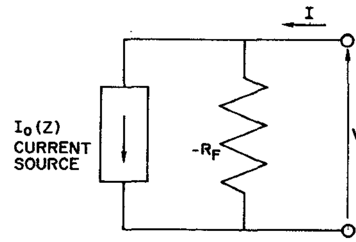

Fig. 6. Simplified dc equivalent circuit for Gunn-flange oscillator above threshold.

Such approximations have been widely used to model the velocity-electric-field characteristics [11]–[13] as well as the current-voltage characteristics [2] of Gunn devices. The present approximation differs in that it models the oscillator characteristics as seen through the low-pass filter of a Gunn flange attached to a cavity and in its use of a single line segment with negative differential-resistance slope to approximate the active region of the Gunn-flange oscillator. This line segment is specified mathematically by

$$I = I_0(Z) - V_F/R_F \tag{1}$$

where I and V_F are the current and voltage, respectively, of the Gunn-flange oscillator and $-1/R_F$ is the negative slope of the line segment with the units of one over ohms. The I_0 is the current axis intercept which varies with changes in the microwave load Z when samples are inserted into the cavities. The equivalent circuit corresponding to this equation is a microwave load-dependent current source in parallel with a negative resistance $-R_F$ as shown in Fig. 6. Using the previous equation to specify the flange oscillator and utilizing Kirchhoff's voltage law for a device in series with a dc supply voltage V_s and a dc bias resistor R_B gives the flange-oscillator voltage V_F as a function of microwave load as

$$V_F(Z) = \frac{V_s - I_0(Z)R_B}{1 - R_B/R_F}. \tag{2}$$

If the supply voltage V_s is held constant and the microwave load is changed (from Z_0 to Z' by sample insertion) then the voltage change is given by

$$\Delta V_F = V_F(Z') - V_F(Z_0) = -\frac{R_B}{1 - R_B/R_F}\Delta I_0 \tag{3}$$

where $\Delta I_0 = I_0(Z') - I_0(Z_0)$. The previous expression for the dc voltage change ΔV_F is seen to be in agreement with Takayama's [3] more general expression for the ac Doppler voltage after noting the equivalence of our ΔV_F, R_B, and R_F with his δV_B, $1/G_B$, and $\partial V_B/\partial I$, respectively [3, eq. 18].

Using this piecewise linear approximation one can specify the allowable values of R_B. If the dc load line [10] is drawn on the graph of Fig. 3, its voltage intercept would be the supply voltage V_s and its slope would be $-1/R_B$. At low supply voltages it would intersect the device curve in the positive-resistance region. As the supply voltage is increased the operating point specified by the intercept would move up toward the peak of the flange-oscillator current value. If $R_B < R_F$, increasing the supply voltage further will result in the two lines intersecting in the active (negative differential resistance) region. However, if $R_B > R_F$, the load line can never intersect the flange-oscillator curve as approximated by the straight-line segments past the peak since the load-line slope would be less than the $1/R_F$ slope. Practically speaking, R_B must be restricted to values considerably

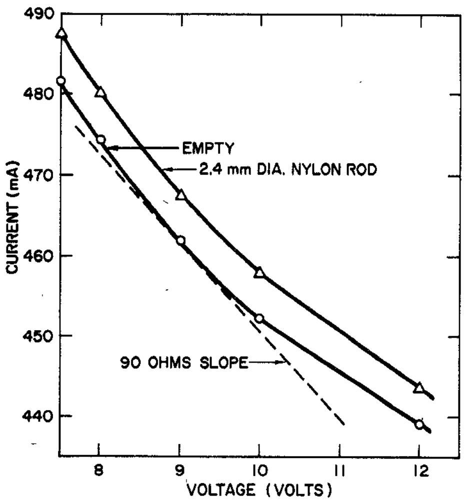

Fig. 7. Shift in the I–V characteristics above threshold for the modified G0(X)-107 Gunn flange attached to the cylindrical cavity when a nylon rod is inserted. The dashed straight line gives the slope of these curves at 9-V bias.

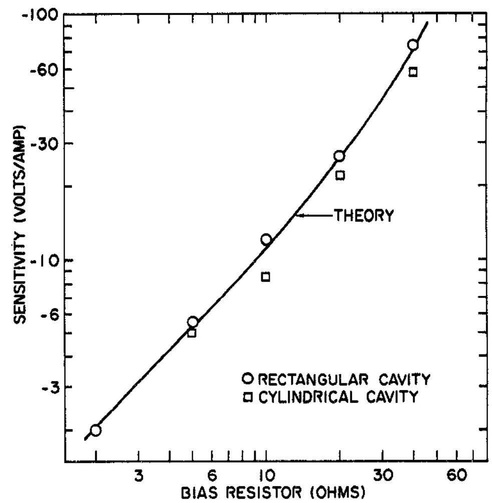

Fig. 8. Sensitivity $\Delta V_F/\Delta I_0$ as a function of bias resistance theory and experiment. Circle data points are for 1-in rectangular cavity and the G0(X)-104 flange. Rectangular data points are for the cylindrical cavity and the modified G0(X)-107 flange.

less than R_F because of the hump of the oscillator characteristic curve above the straight-line approximation near the peak (in the 4- to 5-V region) as seen in Fig. 3. If a load line is drawn tangent to this hump so that it just intersects the oscillator curve at the maximum allowed Gunn-flange voltage (which was 12 V for the two flanges used in this study), one obtains a value for this R_B of approximately 40 Ω. With such an R_B value in series with the supply voltage, the flange voltage will increase slowly as V_s is increased for V_F values below 4 V. If V_s is increased further, the flange-oscillator voltage will suddenly jump from about 4–5 V to 12 V. If any larger R_B value were used, the sudden jump would be to a value exceeding the maximum allowed voltage with probable device damage resulting. Thus R_B could not practically exceed about 40 Ω even though the straight-line slope of Fig. 3 specifies an R_F of between 80 and 90 Ω.

A comparison of this phenomenological theory with experiment can be obtained by varying the bias-resistor value R_B and measuring its effect on the flange voltage ΔV_F. According to (3) the sensitivity $\Delta V_F/\Delta I_0$ should vary as

$$\frac{\Delta V_F}{\Delta I_0} = -\frac{R_B}{1 - R_B/R_F}. \tag{4}$$

The I–V curve for the modified G0(X)-107 flange attached to the cylindrical cavity as shown in Fig. 7 shows that ΔI_0 is 5.2 mA at the 9.0-V bias point when a 2.4-mm-diam nylon sample is introduced into the cavity. Taking the tangent to these two curves at this bias point gives an R_F value of 90 Ω, as indicated by the dashed line of the figure. Bias-resistor values between 5 and 40 Ω were used and ΔV_F was measured when the sample was inserted. As the R_B values were increased, the supply voltage V_s was also increased to maintain the empty-cavity value of V_F at 9.0 V. The resulting $\Delta V_F/\Delta I_0$ values are plotted as the square data points in Fig. 8. For comparison the theoretical value specified by (4) is plotted as the solid line and shows good agreement with the experimental values.

A more precisely controlled microwave load was obtained by connecting the 1-in-long rectangular cavity and G0(X)-104 Gunn-flange oscillator to a precision rotary vane X-band waveguide attenuator terminated by a short so that the amplitude of the microwave signal reflected from the short could be precisely varied. Changing the attenuator from 0 to 0.2 dB gave a ΔI_0 of -1.3 mA and a flange-oscillator I–V curve whose tangent at the operating point had an R_F value of approximately 90 Ω. The experimental values of $\Delta V_F/\Delta I_0$ obtained with this system for R_B values between 2 and 40 Ω are shown by the round data points of Fig. 8. They agree even more closely with the theoretical curve. This agreement supports the validity of the equivalent-circuit model of Fig. 6 for modeling flange-oscillator behavior.

IV. Discussion

It has been shown that physical properties like size of dielectric samples can be measured without mechanical contact with the samples by inserting them into Gunn-flange microwave oscillators. This measurement is simply accomplished by monitoring only the dc current or voltage supplied to the Gunn flange of the oscillator. The reason that makes such simple detection possible has been identified as a shift in the Gunn-flange-oscillator I–V characteristics in the active region when the microwave impedance is changed by introducing a sample into the cavity. A piecewise linear approximation of the dc characteristic leads directly to an active-region equivalent-circuit model of the flange oscillator as a microwave load-dependent current source in parallel with a negative resistance. This model predicts a dependence of detection sensitivity on bias resistance that explains the restrictions on the maximum allowable value for the series bias resistor. Typical experimental data on two different Gunn-device flanges and three oscillator cavities have been presented to demonstrate that the described properties are characteristic of a range of Gunn-flange oscillators.

The use of a current source to model the microwave-frequency properties of Gunn devices has been presented by Robrock [14], [15] and by Khandelwal and Curtice [16]. The change in the average current flowing through such devices as we have reported in this short paper is in qualitative agreement with the results of Khandelwal and Curtice. These workers found that the complex admittance for Gunn devices operating in their active region varied with the amplitude of the microwave signal. Insertion of samples into the oscillator undoubtedly affects the signal amplitude since Gunn-oscillator power output depends strongly on the microwave frequency as well as on cavity losses [1]. Thus the average current should also vary with sample insertion, because this would change the microwave-signal amplitude and the device admittance. Descriptions of such variations in Gunn-device terminal current with changing operation conditions have also been described by Mizushina and Takao [17].

The hysteresis that limited measurement accuracy in these experiments may have been due to thermal effects. The power density that must be dissipated in Gunn devices is extremely high so that the operating temperature in the bulk of the Gunn device is elevated to values well above ambient. Thus any small change in average dc current input could cause significant changes in the device temperature and its operational characteristics which would lead to hysteresis.

The microwave load-dependent current variations reported here may be much stronger with Gunn oscillators than with IMPATT oscillators. When an IMPATT diode was used to replace the Microwave Associates Gunn device in the Gunn flange, microwave oscillations were obtained when the IMPATT was properly biased and the flange was connected to a cavity. However, insertion of the $\frac{1}{8}$-in-diam Teflon sample resulted in no detectable change in the average dc current flowing through the flange as monitored by a digital ammeter with 10-μA resolution.

Acknowledgment

The authors wish to thank M. R. Lakshminarayana for his valuable assistance in locating relevant references referred to throughout this short paper. Other important references were pointed out by the Transactions reviewers, and helpful comments on possible explanations of the observed phenomena were also provided by them.

References

[1] H. Pollman, R. Englemann, W. Frey, and B. Bosch, "Load dependence of Gunn-oscillator performance," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 817–827, Nov. 1970.
[2] S. Nagano and Y. Akaiwa, "Behavior of Gunn diode oscillator with a moving reflector as a self-excited mixer and load variation detector," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 906–910, December 1971.
[3] Y. Takayama, "Doppler signal detection with negative resistance oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 89–94, February 1973.
[4] T. Nygren and A. Sjolund, "Sensitivity of Doppler radar with self-detecting diode oscillators," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-22, pp. 494–498, May 1974.
[5] J. Bybokas and B. Farrell, "The Gunn flange—A building block for low-cost microwave oscillators," *Electronics*, vol. 44, pp. 47–50, March 1, 1971.
[6] T. P. Lee and R. D. Standley, "Frequency modulation of a millimeter-wave IMPATT diode oscillator and related harmonic generation effects," *Bell System Tech. J.*, vol. 48, pp. 143–161, January 1969.
[7] W. M. Sharpless, "Wafer-type millimeter wave rectifiers," *Bell Syst. Tech. J.*, vol. 35, pp. 1385–1402, Nov. 1956.
[8] A. J. Baden Fuller, *Microwaves.* Oxford: Pergamon Press, 1969, pp. 127–128.
[9] A. A. Sweet, "How to build a Gunn oscillator," *Microwave Systems News*, vol. 3, pp. 32–38, October–November 1973.
[10] D. L. Schilling and C. Belove, *Electronic Circuits: Discrete and Integrated.* New York: McGraw-Hill, 1968, pp. 22–25.
[11] H. L. Grubin, M. P. Shaw, and P. R. Solomon, "On the form and stability of electric-field profiles within a negative differential mobility semiconductor," *IEEE Trans. Electron Devices*, vol. ED-20, pp. 63–78, Jan. 1973.
[12] J. E. Carroll, *Hot Electron Microwave Generators.* London: Edward Arnold Ltd., 1970, pp. 85 and 98.
[13] G. S. Kino and I. Kuru, "High-efficiency operation of a Gunn oscillator in the domain mode," *IEEE Trans. Electron Devices*, vol. ED-16, pp. 735–748, Sept. 1969.
[14] R. B. Robrock, II, "A lumped model for characterizing single and multiple domain propagation in bulk GaAs," *IEEE Trans. Electron Devices*, vol. ED-17, pp. 93–102, Feb. 1970.
[15] ——, "Extension of the lumped bulk device model to incorporate the process of domain dissolution," *IEEE Trans. Electron Devices*, vol. ED-17, pp. 103–107, Feb. 1970.
[16] D. D. Khandelwal and W. R. Curtice, "A study of the single-frequency quenched-domain mode Gunn-effect oscillator," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-18, pp. 178–187, April 1970.
[17] S. Mizushina and I. Takao, "Representation of Gunn diodes by parallel combination of nonlinear conductance," *Proc. IEEE*, vol. 61, pp. 137–138, Jan. 1973.

A Variable Directional Coupler Using InSb Thin Films

IKUO TANAKA, MEMBER, IEEE, AND MASAHIDE OHSHITA

***Abstract*—A variable directional coupler whose coupling is varied by an applied dc magnetic field is presented in this short paper. The directional coupler is of the two-hole type having InSb thin films in the coupling apertures to which the magnetic field is applied perpendicularly. The directional coupler was tested at room temperature at frequencies from 32 to 36 GHz. At a frequency of 33.1 GHz and magnetic flux densities of up to 13 kG, the coupling varies from 14.2 to 40.2 dB with the directivity exceeding 24.6 dB, the insertion loss of about 1 dB, and the VSWR of 1.2.**

Introduction

One sometimes encounters inconvenience in laboratory work because the coupling of the directional coupler is too loose or too tight, or it changes with frequency, or the power from the source fluctuates with frequency. A variable directional coupler certainly offers a convenient alternative in such circumstances. Variable directional couplers, including the Bethe's hole coupler, the slab-line-type coupler, the circular-electric-type coupler, and so on, have been developed. However, they employ a moving mechanism, which calls for a tight mechanical tolerance and tends to limit their practical applications.

A variable directional coupler whose coupling is varied by means of applied dc magnetic field has been developed by using InSb thin films in two coupling apertures to achieve variable coupling. Microwave devices such as the isolator have been developed by using thin InSb samples [1]–[5]. A drawback common to these devices is a rather high insertion loss.

The thin InSb films used in the present work, which are prepared by the controlled evaporation method [6], have a thickness of about 1 μm. The small thickness combined with high electrical qualities of the films results in a reduced insertion loss as well as a low dc magnetic field.

Structure of the Variable Directional Coupler

The structure of the variable directional coupler is illustrated in Fig. 1. Referring to Fig. 1(a), a part of the power incident on port I is coupled out from port II by means of a pair of coupling rectangular apertures cut along the center line of the common broad wall of the waveguides with a separation of about three quarters of a guide wavelength. Unlike the conventional two-hole coupler, thin InSb films are placed in the coupling apertures, as detailed in Fig. 1(b) and (c). An external magnetic field is applied perpendicularly to the films to vary the coupling. The prototype model described in this short paper employs the WRJ-320 waveguide (inside dimensions: 7.112 × 3.556 mm; outside dimensions: 9.14 × 5.59 mm) and two InSb films having slightly different dimensions: $a = 2.77$, $b = 1.74$, $c = 1.02$ for A-1 and $a = 2.75$, $b = 1.65$, $c = 1.02$ mm for A-2. The coupling rectangular apertures measure 0.70 × 1.98 for A-1 and 0.70 × 2.05 mm for A-2, respectively. The film dimensions were determined by a cut-and-try procedure to maximize the directivity over a frequency range from 32 to 36 GHz. The films were prepared by evaporating InSb onto a cleaved mica sheet about 200 μm thick, and covered by another mica sheet for protection.

Manuscript received May 12, 1975; revised March 15, 1976.
The authors are with the College of Engineering, Shizuoka University, Hamamatsu 432, Japan.