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.

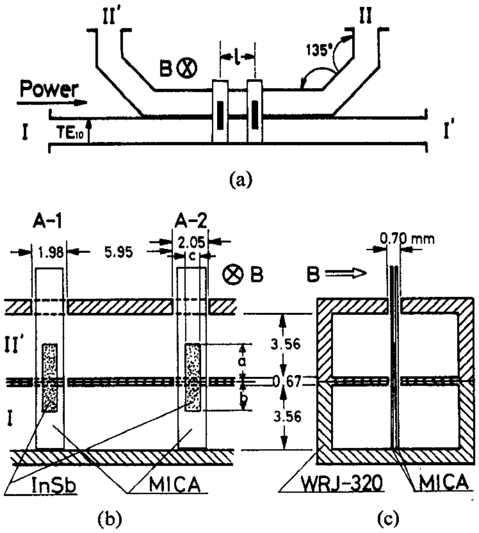

Fig. 1. Structure of the variable directional coupler. (a) Schematic. (b) and (c) Side view and front view of the coupling structures. (B = magnetic field, l = 8.40, a = 2.77, b = 1.74, c = 1.02 mm for A-1 and a = 2.75, b = 1.65, c = 1.02 mm for A-2.)

The film has a 1.0-μm thickness and the following properties: the Hall mobility is 2.5×10^4 $cm^2/V \cdot s$; the Hall coefficient is 294 cm^3/C; the carrier density is $2.12 \times 10^{16}/cm^3$; and the conductivity is $85/\Omega \cdot cm$.

Experimental Results

Performance of the coupler can be described in terms of the coupling C, directivity D, input VSWR, and insertion loss L in the primary waveguide as functions of the applied magnetic field and the operating frequency.

These parameters of the prototype coupler were measured at room temperature by the methods given in [7] and [8]. Results are presented in Figs. 2 and 3, which show dependence on the magnetic field and the frequency, respectively.

Measurements made at a frequency of 33.1 GHz, shown in Fig. 2, indicate that the coupling C is variable from 14.2 to 40.2 dB by adjustment of the dc magnetic field from 0 to 13 kG, giving an average slope of 2 dB/kG. With no InSb films in the coupling apertures, the structure gives a coupling of about 55 dB or more. The coupling at low magnetic field is strongly dependent on electronic properties of the InSb film as well as the shape and dimensions of the coupling apertures and the films. Dependence of C on the magnetic field shows a strong resemblance to that of the magnetoresistance [6], [9], indicating that the magnetoresistance effect in the InSb films in the apertures is at work to achieve the variable coupling. Hence the device is reciprocal with respect to the direction of the applied magnetic field.

The directivity D decreases from 29.8 to 24.6 dB as the magnetic field increases from 0 to 13 kG, though it is desirable that D remain constant at a high value. However, the minimum value of 24.6 dB may be regarded sufficiently high for many applications. With no InSb films in the apertures, it was not possible to measure the directivity, for the backward output power from port II' was below the threshold of the instrument sensitivity.

The input VSWR is roughly constant, as shown in Fig. 2.

The frequency characteristics of the device were measured at frequencies from 32 to 36 GHz, which were limited by the source available at our laboratory. Results are presented in Fig. 3, where the solid and dotted lines correspond to magnetic fields of 0 and 5 kG, respectively.

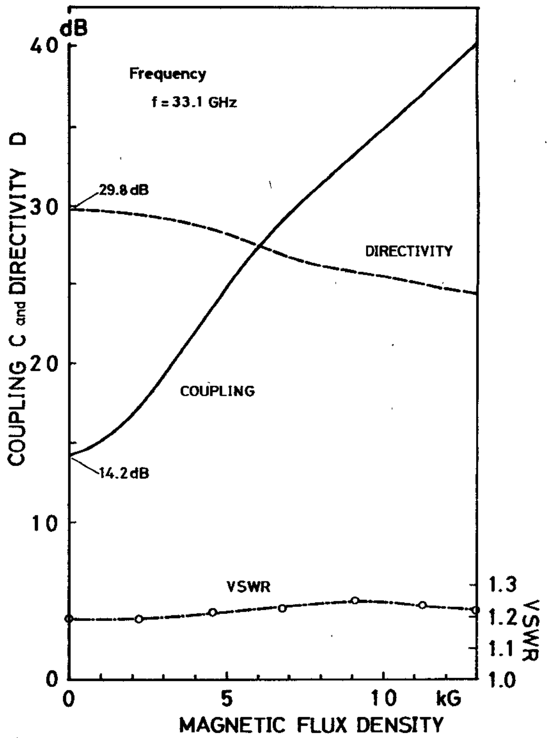

Fig. 2. The coupling, the directivity, and the input VSWR as a function of magnetic flux density at a frequency of 33.1 GHz.

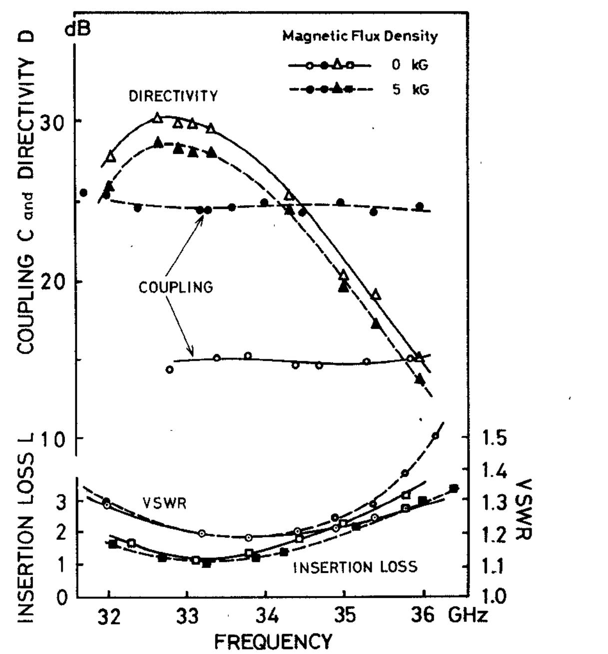

Fig. 3. The coupling, the directivity, the input VSWR, and the insertion loss versus the frequency of operation. The magnetic flux density is taken as the parameter; solid line at zero and dotted line at 5 kG.

The coupling C varies little with the frequency, and its deviation is within ± 0.5 dB over the band of frequency.

The directivity D varies parabolically from 25.9 dB at 32.1 GHz to 13.7 dB at 35.8 GHz at the magnetic field of 5 kG. However, the minimum value of 13.7 dB may be regarded acceptable for most of the applications. As the directivity depends strongly on the balance of the couplings of two apertures as well as l in Fig. 1(a), the couplings should be made approximately the same to achieve a high directivity. The particular design shown in Fig. 1 is a result of a compromise between the directivity and the bandwidth of the device obtained through a cut-and-try procedure. During the optimization procedure, it was possible to obtain a 36-dB directivity for a much narrower bandwidth of around 33.1 GHz. To achieve a good directivity by using the hole-type coupler over a wide band of frequencies, a coupler with many apertures which have InSb films should be used.

The input VSWR stays below 1.4 over the frequency range from 32 to 36 GHz.

The insertion loss L has the minimum value of 1.0 dB at about 33.2 GHz and 2.5–3 dB at 36 GHz, depending on the applied magnetic field. Although these L values are smaller than the reported values of the insertion loss of other microwave devices using InSb [1], [2], [4], [5], it may be required to reduce the L value and its dependency on the magnetic field for certain applications of the coupler. Our experience shows that L increases with the thickness of the InSb film. The thinnest film that can be prepared by our present technique without sacrificing its electrical properties is about 1 μm.

An inspection of Fig. 3 shows that the coupler has a center frequency of operation at about 33 GHz. This is slightly below the design value of 34.1 GHz at which the separation l of the coupling apertures, referring to Fig. 1, corresponds to three quarters of a guide wavelength. The slight discrepancy may be attributed to the presence of the mica sheets and the finite thickness of the coupling apertures.

The device performance was independent of the input-power level up to 20 mW, which was the limit of the source available at our laboratory.

Conclusion

The results obtained for the variable directional coupler at room temperature may be summarized as follows: 1) the coupling varies from 14.2 dB at a 0 magnetic flux density to 40.2 dB at 13 kG, with an average slope of 2 dB/kG; 2) the directivity is larger than about 14 dB over the frequency band of 32–36 GHz; 3) the insertion loss is 1–3 dB for an InSb film thickness of 1 μm; and 4) the variable coupling appears to be achieved by the magnetoresistance effect in the InSb films in the coupling apertures.

Problems left for future studies include: 1) finding relationships between performance characteristics of the coupler and the properties of InSb films; 2) achieving a high directivity over a wide band of frequencies; 3) assessment of the temperature dependence; 4) reduction in the insertion loss; and 5) theoretical analysis to optimize design.

The authors consider that the directional coupler described in this short paper is usable for the shorter millimeter waves, for it employs the evaporated InSb thin films that require a relatively low magnetic field and offer a low insertion loss. The principle also offers a method of trimming the fixed directional coupler with the aid of a permanent magnet, relaxing mechanical tolerance requirements.

Acknowledgment

The authors wish to thank Prof. T. Okabe and Prof. S. Mizushina of Shizuoka University, and Prof. K. Ura of Osaka University for their encouragement in this work.

References

[1] K. Suzuki, "Room temperature solid-state plasma nonreciprocal microwave devices," *IEEE Trans. on Electron Devices*, vol. ED-16, pp. 1018–1021, Dec. 1969.
[2] K. Suzuki and R. Hirota, "Nonreciprocal millimeter-wave devices using a solid-state plasma at room temperature," *IEEE Trans. on Electron Devices*, vol. ED-18, pp. 408–411, July 1971.
[3] D. J. White, "Room-temperature Faraday rotation in n-type InSb films at 23.4 GHz," *J. Appl. Phys.*, vol. 39, pp. 5083–5086, Oct. 1968.
[4] T. Okabe, M. Ohshita, and S. Shinohara, "Millimeter-wave isolators with low magnetic field using a thin vacuum-deposited film of InSb," *Trans. IECE of Japan*, vol. 57-B, pp. 244–249, Apr. 1974.
[5] R. J. Dinger, T. M. Waugh, and D. J. White, "Nonreciprocal properties of vacuum-deposited InSb films at 87 GHz," *IEEE Trans. on Microwave Theory Tech.*, vol. MTT-22, pp. 879–880, Oct. 1974.
[6] M. Ohshita, "High electron mobility InSb films prepared by source-temperature-programed evaporation method," *Jap. J. Appl. Phys.*, vol. 10, pp. 1365–1371, Oct. 1971.
[7] R. Levy, *Advances in Microwaves*, vol. 1. New York: Academic Press, 1966.
[8] M. Sucher and J. Fox, *Handbook of Microwave Measurements*, vol. II. New York: Polytechnic Press, 1963.
[9] H. H. Wieder and D. J. White, "Microwave magnetoresistance of dendritic N-type InSb films," *J. Appl. Phys.*, vol. 39, pp. 2401–2407, Apr. 1968.

The Segmentation Method—An Approach to the Analysis of Microwave Planar Circuits

T. OKOSHI, MEMBER, IEEE,
Y. UEHARA, AND T. TAKEUCHI

Abstract—**In many practical planar circuitries, the circuit pattern can be divided into several segments which themselves have simpler shapes such as rectangles. The segmentation method proposed in this short paper is a method in which the characteristics of a planar circuit are computed by combining those of the segmented elements. It features a relatively short computer time required. The principle and computer algorithm are described. Finally, as an example, the application of the proposed method to the trial-and-error optimum design of a ladder-type 3-dB hybrid is described.**

I. Introduction

A planar circuit is a 2-dimensional circuit that should be classified between the distributed-constant (1-dimensional) circuit and waveguide (3-dimensional) circuit. It is defined as an electrical circuit having dimensions comparable to the wavelength in two directions, but much less thickness in one direction [1].

Several methods have been known for the analysis of planar circuits. When the circuit pattern is as simple as square, rectangular, circular, or annular, the impedance matrix can be obtained in a series-expansion form from the Green's function of the wave equation [1]. When the circuit pattern is more arbitrary, the numerical analysis based upon the contour-integral representation of the wave equation is most efficient [1]. Other numerical approaches applicable to arbitrary circuit patterns are the variational method, relaxation method, and the finite-element method [2].

When the circuit pattern is entirely arbitrary, we must rely upon one of those numerical analyses. However, in actual planar circuitry, an entirely arbitrary circuit pattern is not very common; in many cases the pattern consists of several "segments," which themselves have simpler shapes such as rectangles.

The "segmentation method" proposed in this short paper is a method in which the characteristics of a planar circuit are

Manuscript received December 24, 1975; revised April 2, 1976.
The authors are with the Department of Electronic Engineering, University of Tokyo, Bunkyo-ku, Tokyo 113, Japan.