20-GHz Band Monolithic GaAs FET Low-Noise Amplifier

ASAMITSU HIGASHISAKA AND TAKAYUKI MIZUTA

***Abstract*—A 20-GHz band monolithic GaAs FET low-noise amplifier has been developed. Design and fabrication were performed by obtaining the transmission properties of the microstrip lines on a semi-insulating GaAs substrate. The developed monolithic amplifier consists of a submicron gate GaAs MESFET and the input and output distributed matching circuits on a semi-insulating GaAs substrate measuring 2.75 mm×1.45 mm. A noise figure of 6.2 dB and an associated gain of 7.5 dB were obtained at 21 GHz without any additional tuning adjustments.**

I. Introduction

MUCH PROGRESS has been made in *C*- and *X*-band GaAs MESFET's in the past several years [1]–[4], and some of the parametric amplifiers and traveling wave tubes are being replaced by GaAs MESFET's [1], [4]. On the other hand, demands for GaAs FET amplifiers operating at *K*-band or higher are increasing for satellite communication systems applications. One problem is how the input and output matching circuits should be realized to exhibit the inherent superiority of GaAs MESFET at such a high frequency range. A decrease in the wavelength inevitably requires good accuracy of the pattern size for the matching circuits; for example, a small error in the length of the bonding wires brings about a serious deterioration in the microwave performance. As long as distributed or lumped element circuits constructed on alumina substrates are used in the conventional manner, it is difficult to obtain a good performance with a reasonable reproducibility.

In order to overcome these problems, monolithic GaAs FET amplifiers have been proposed and demonstrated [5]–[7], where in all active and passive elements are integrated on a semi-insulating substrate. In this approach, all bonding wires are eliminated and a fine matching circuit pattern is obtainable because the refined techniques developed for GaAs MESFET's are used for the fabrication of the matching circuits.

The merit of the monolithic approach is enhanced at higher frequency ranges than *K*-band, because the matching circuit on the GaAs substrate becomes smaller for higher frequencies. Most of the previous reports are, however, concerned with *X*-band amplifiers [5], [7].

The purpose of this paper is to demonstrate a *K*-band (20-GHz) monolithic GaAs FET low-noise amplifier, whose matching circuits are formed in a distributed form on a semi-insulating substrate. In order to obtain the fundamental data which are necessary in designing the distributed circuits on a semi-insulating GaAs substrate, the dielectric constant ϵ_r of GaAs crystal and the transmission properties of the microstrip line such as the characteristic impedance (Z_0) the slow-wave factor (λ_g/λ_0) and the attenuation constant (α) were also investigated. These fundamental data are shown in the next section. Section III shows the design and the fabrication process of a 20-GHz band GaAs FET monolithic low-noise amplifier. The microwave performance—power gain (G_a), noise figure (NF_{min}) and their frequency response—is shown in Section IV.

II. Measurements of Transmission Properties of Microstrip Lines on an SI GaAs Substrate

The semi-insulating (SI) GaAs substrate was confirmed to be a low-loss high-permittivity medium suitable as a substrate for microstrip lines. In order to obtain the fundamental data for the design of microstrip lines on a SI GaAs substrate, the dielectric constant (ϵ_r) of SI GaAs substrate and the transmission properties of the microstrip lines such as the characteristic impedance, the wavelength and the attenuation constant are measured. In the experiments, Cr-doped SI GaAs substrate having resistivity of more than 10^8 $\Omega \cdot$cm are used. Strip conductors were prepared by vacuum evaporation of Cr (600 A)/Au (2000 A) film followed by Au-plating of about 3 μm in thickness. Measurements were carried out for the frequency range of 2–12 GHz.

A. Relative Dielectric Constant (ϵ_r) of SI GaAs

The relative dielectric constant (ϵ_r) is an important parameter for the substrate medium of a microstrip line. Several measurements on ϵ_r of GaAs have been reported so far [8], [9] giving ϵ_r measurements of 10 to 13. In this work, in order to ascertain the previous data and to get a basic datum for the design of the microstrip lines, the relative dielectric constant ϵ_r of up to data GaAs substrate was obtained by measuring the resonant frequency of rectangular blocks of SI GaAs [10]. The basic resonator structure is shown in the inset of Fig. 1, where the two broad faces are metalized with Cr–Au film, but the side walls are left uncoated. The resonant frequencies were measured over the frequency range of 2 to 12 GHz by

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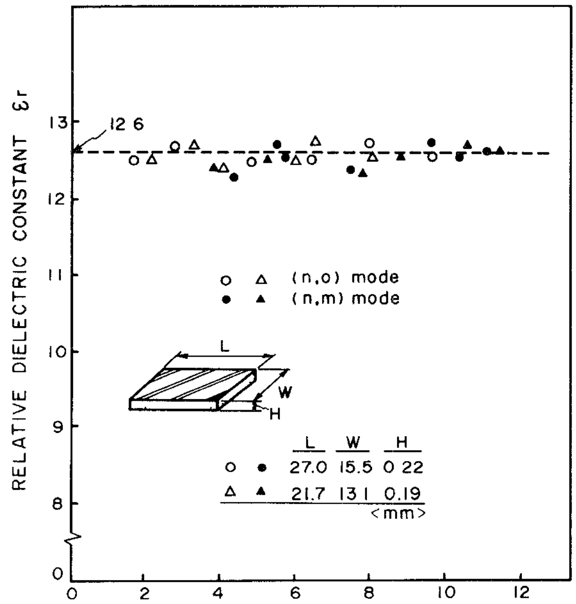


Fig. 1. Measured relative dielectric constant ϵ_r of semi-insulating GaAs.

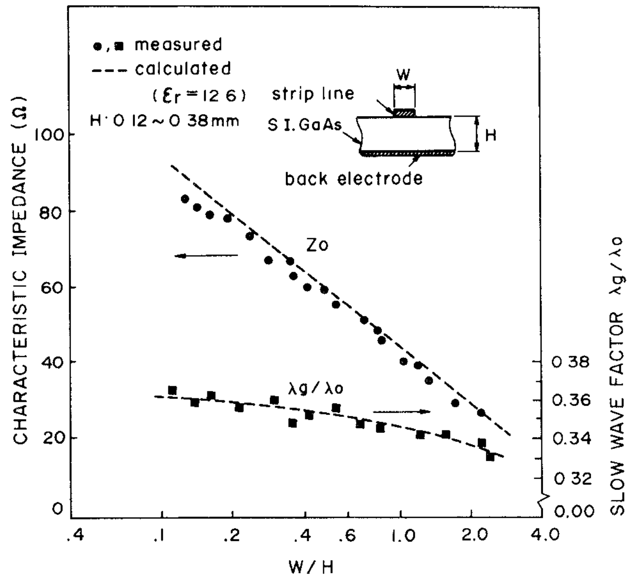


Fig. 2. Characteristic impedance Z_0, slow-wave factor λ_g/λ_0 versus dimensions of the microstrip lines constructed on SI GaAs substrate.

observing sharp minima on the transmission spectra with a Hewlett-Packard network analyzer.

The ϵ_r obtained is illustrated in Fig. 1 as a function of the resonant frequency. There are some scatter in the measured points, which is probably due to a coupling error [10], but the relative dielectric constant of SI GaAs is found to be about 12.6. This value agrees well with that recently measured by Neidert [9].

B. Characteristic Impedance (Z_0) and Slow-Wave Factor (λ_g/λ_0)

The relationship between the microstrip line size and the characteristic impedance is important in designing the actual microstrip circuits. The characteristic impedance was obtained by treating a sample as a $\lambda_g/4$ transformer. From the real part (R_I) of the input impedance of the sample terminated with 50-Ω load at the resonant frequency, the characteristic impedance (Z_0) was calculated by the following equation:

$$Z_0 = (R_I\, 50)^{1/2}. \tag{1}$$

In our experiments, R_I was measured for a lot of samples with different linewidths (W), and with different substrate thicknesses (H) for the frequency range of 1.5 to 4 GHz.

Solid circles in Fig. 2 show the measured characteristic impedance as a function of the linewidth to the substrate thickness ratio (W/H). The broken line represents the theoretical one [11] given calculated by assuming ϵ_r to be 12.6. Experimental and the theoretical results show a good agreement, indicating that the dielectric constant of 12.6 can be adopted in designing the microstrip lines on a SI GaAs substrate.

Another important factor which is indispensable in designing the actual microstrip circuits is the wavelength in the microstrip line. The wavelength was measured by observing the resonant frequency of a half-wavelength microstrip line for the frequency range of 3.8 to 8.2 GHz. The measured wavelength (λ_g) normalized by the free space wavelength (λ_0)—slow-wave factor—is shown in Fig. 2 by solid rectangles. Measured λ_g/λ_0 agrees well with the theoretical one (broken line).

By using the experimental or theoretical results predicted in Fig. 2 the actual microstrip lines are designed. For example, the W/H value which gives Z_0 of 50 Ω is about 0.75, that is, when the substrate thickness is 200 μm, the linewidth is 150 μm. The slow-wave factor is, in this case, about 0.35. A wavelength at 20 GHz is calculated from the slow-wave factor to be about 5.25 mm.

C. Attenuation Constant (α)

Attenuation constant of the microstrip lines constructed on a SI GaAs substrate was measured and compared with that of microstrip lines on an alumina substrate. In this work, the attenuation constant was derived from the unloaded Q-value of a half-wavelength microstrip resonator. Fig. 3 shows the attenuation per wavelength of samples with different linewidths and substrate thicknesses as a function of the measured frequency. Since the matching circuit becomes smaller for a higher frequency, the attenuation per wavelength ($\alpha\lambda_g$) is adopted in the figure. The thickness of the strip conductor (Au) is about 3 μm.

The attenuation ($\alpha\lambda_g$) of the microstrip line with 50-Ω characteristic impedance constructed on 0.38-mm thick SI GaAs substrate is about 0.185 dB at 4 GHz and 0.13 dB at 15 GHz, these values are almost the same as those of the microstrip line constructed on the alumina substrate. It is confirmed from this experimental result that the dielectric loss of SI GaAs is as small as that of the alumina substrate and the transmission loss of the microstrip line is almost that of the conductor.

It should be noted that the conductor loss is greater for

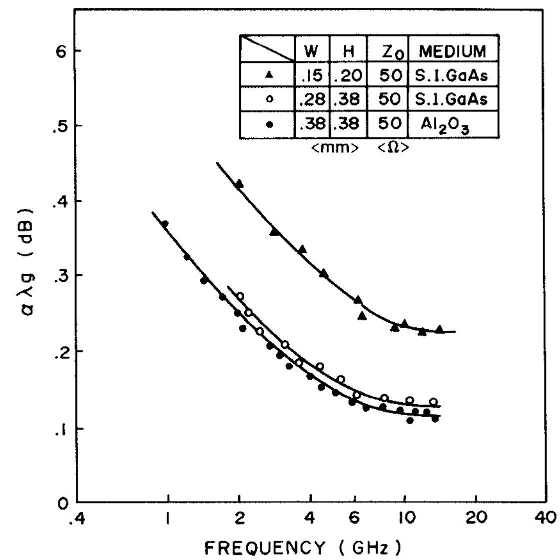


Fig. 3. Relationship between the transmission loss and frequency measured on microstrip lines constructed on a SI GaAs substrate and on a Al_2O_3 substrate.

microstrip lines with a narrower linewidth on a thinner substrate. However, even for the practical SI GaAs microstrip line with the substrate thickness of 0.2 mm ($Z_0 = 50$ Ω), the attenuation per wavelength is about 0.22 dB at 15 GHz and higher frequencies. This is small enough from a practical point of view.

III. Design and Fabrication of Monolithic GaAs FET Amplifier

A. Design of Monolithic Amplifier

The merit of a monolithic GaAs FET amplifier is enhanced at higher frequencies such as *K*-band, because 1) the matching circuit can be made smaller for higher frequencies [7], and 2) it is not easy to construct such a high-frequency amplifier in a conventional manner. From these points of view, a 20-GHz band monolithic GaAs FET low-noise amplifier was adopted in this work to demonstrate its feasibility.

In order to obtain an adequate gain at 20-GHz band, a low-noise high-gain GaAs MESFET with a submicron gate was required as an active device. We have already developed submicron gate low-noise FET (NE388) [10]. The GaAs MESFET used in the monolithic amplifier was designed in the same manner as the previous discrete device having a carrier density of $2.0-2.5 \times 10^{17}$ cm^{-3} and a pinch-off voltage of 1.5–2.5 V. The gate width is 140 μm (one-half of NE388). Equivalent circuit of the developed monolithic amplifier is shown in Fig. 4. The matching circuits are constructed with microstrip lines and parallel tuning stubs.

The matching circuits were determined using a Smith Chart based on the small-signal *S*-parameters (S_{11}, S_{22}) of the active device. Fig. 5 shows the frequency loci of the input and output impedance of the active device, which were derived from the measured *S*-parameters of the

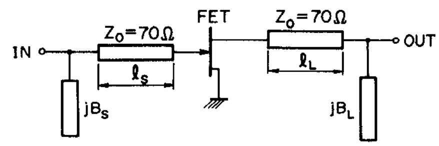


Fig. 4. Equivalent circuit of a 20-GHz band monolithic low-noise amplifier.

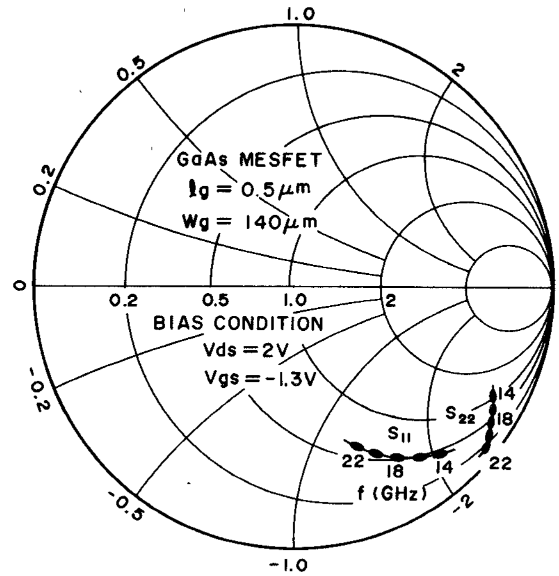


Fig. 5. Small-signal *S*-parameters (S_{11}, S_{22}) of a 0.5-μm gate low-noise GaAs MESFET with a gate width of 140 μm.

discrete device (NE388) by subtracting the bonding wire inductance and by doubling the impedance values.

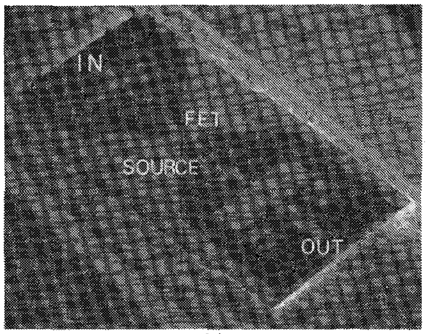
The input and output matching circuits were designed not to achieve the wide-band operation, but to get the maximum gain at 20 GHz, since the main objective of this work is to test the feasibility of the monolithic approach of a low-noise GaAs FET amplifier at 20 GHz.

The characteristic impedance of the microstrip lines between the active device (GaAs FET) and the parallel tuning stubs were chosen to be 70 Ω by considering both the line length and the transmission loss—high characteristic impedance reduces the line length needed for the same impedance transformation but gives a larger loss. The tuning stubs are capacitive stubs with the length of $\lambda g/8$.

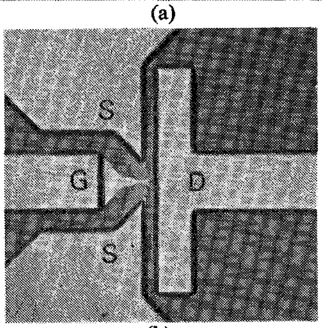
B. Device Fabrication

The basic structure and the fabrication process of the active device used in the monolithic amplifier are almost the same as those of the discrete device [12]. A vapor phase epitaxial layer grown successively on a high-purity epitaxial buffer layer is used. The gate electrode was formed by an aluminum film strip having a length of 0.5 μm and a width of 140 μm. The source and drain ohmic contacts were prepared by alloying a 0.15-μm thick gold–germanium film covered by a thin nickel film.

The strip line conductor was made of a chromium–gold film, which as thickened to 3 μm by gold-plating in order to reduce the conductor loss. At the same time, the source and drain regions were also metalized.



(a)



(b)

Fig. 6. SEM photograph of the 20-GHz band monolithic amplifier constructed on (a) SI GaAs substrate measuring 2.75 mm×1.45 mm, and (b) magnified view of GaAs MESFET portion involved in the monolithic amplifier.

Fig. 6(a) shows the SEM photograph of the 20-GHz band monolithic GaAs FET low-noise amplifier formed on a 2.75-mm×1.45-mm×0.2-mm chip. The FET is in the center of the chip. The magnified photograph of the active FET portion is shown in Fig. 6(b). The 70-μm microstrip lines, are bent rectangularly to reduce the chip length.

The source regions are spreading gradually from the FET portion toward both sides, and grounded via a gold film plated on chip side. This technique, which can reduce the source lead inductance, is very important in obtaining a good performance at K-band and higher frequencies. According to our measurements, the source-ground reactance was about 4 Ω at 20 GHz, which corresponds to the inductance of about 32 pH.

IV. Microwave Performance of the Developed Amplifier

A. Measurements

In the measurements, the input and the output terminals of the amplifier were connected to the external circuits with 50-Ω characteristic impedance with the mesh ribbons. The drain and the gate bias were applied through the dummy ports of the isolators attached at the input and output connectors of the test jig. DC block was achieved by coxial to waveguide transformers.

B. Microwave Performance

Power gain and noise figure response versus frequency of the monolithic GaAs FET low-noise amplifier are shown in Fig. 7 (gate bias dependence) and in Fig. 8

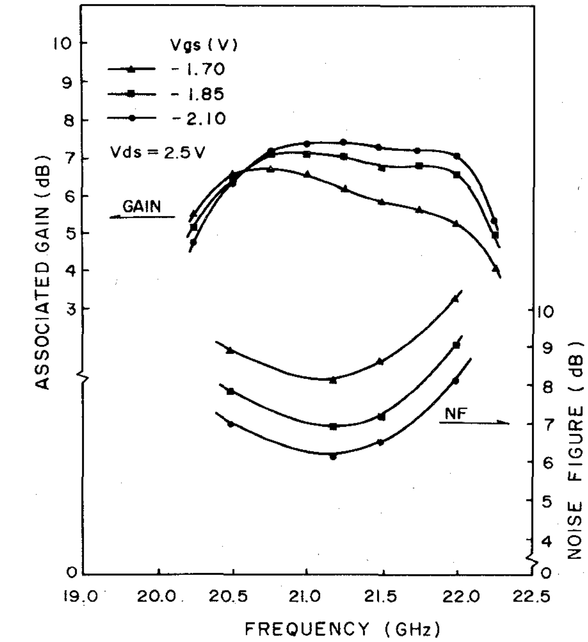


Fig. 7. Power gain and noise figure versus frequency of a monolithic GaAs FET amplifier (gate bias dependence).

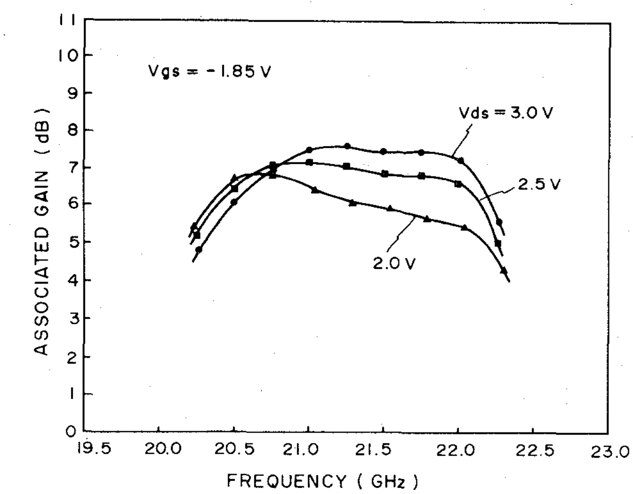


Fig. 8. Power gain response versus frequency as a function of drain bias voltage.

(drain bias dependence). The device is as made and no additional tuning adjustments were made inside or outside the chip. Although the performance degraded at lower gate bias or lower drain bias the following performance was obtained at the bias condition of $V_{ds}=2.5$ V, $V_{gs}=-2.1$ V:

center frequency	$f_c=21.3$ GHz
bandwidth	BW = 1.7 GHz (20.5–22.2 GHz)
minimum noise figure	$NF_{min}=6.2$ dB
associated power gain	$G_a=7.5$ dB.

The center frequency is somewhat higher than the designed value, which is probably due to the fact that the matching circuits were designed by using the S-parameters of the discrete device. The bandwidth was not satisfactory

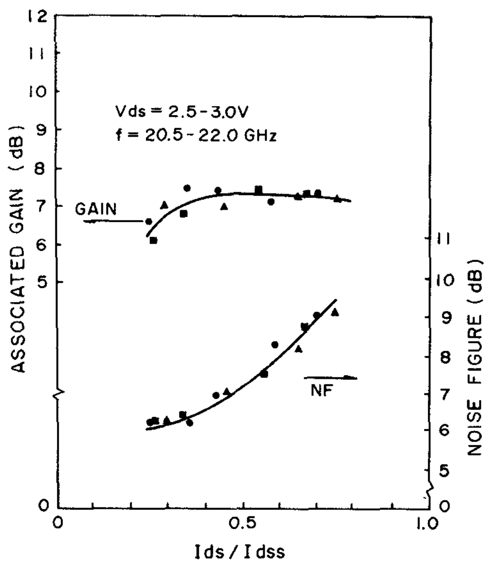


Fig. 9. Drain current dependence of the power gain and the noise figure of a 20-GHz band monolithic amplifier.

enough; this is simply because no attempt was made in the matching circuit design to achieve a broad-band response.

Power gain and noise figure depend more strongly on the gate bias voltage than on the drain bias voltage. Fig. 9 shows the noise figures and associated gains of several chips, as a function of drain current (I_{ds}) normalized to the drain saturation current (I_{dss}). The noise figure was improved with decrease of the drain current and showed a minimum value at the drain current I_{ds} of 0.2 to 0.3 I_{dss}. The best noise figure was 6.2 dB at 21 GHz with an associated gain of 7.5 dB. This performance is comparable or better than that of the conventional 20-GHz band GaAs FET low-noise amplifiers with discrete device [13].

One of the features of the monolithic approach is that it can give an uniform performance with a good reproducibility. According to our measurements on more than twenty chips from different four wafers, the scattering of the center frequency was within ±0.2 GHz, which is only 2 percent deviation. On the other hand, power gain and noise figure showed a little larger scatter of ±0.3 dB as shown in Fig. 9. These differences are probably attributable to the slight difference in the active device's performance, such as the gate length or the carrier concentration.

It is confirmed from these experimental results that, if only the active device (FET) is fabricated uniformly from chip to chip, the monolithic amplifier with a uniform performance can be obtained with a sufficient reproducibility.

V. Summary

It was demonstrated that a 20-GHz band monolithic GaAs FET low-noise amplifier can deliver a comparable or better performance than that of a conventional amplifier with a discrete GaAs FET. It was designed well, and the uniformity of the performance was good (center frequency: ±0.2 GHz; noise figure: ±0.3 dB).

The design and fabrication were performed after measuring transmission properties of the microstrip lines on the semi-insulating GaAs substrate. It was found that the dielectric constant of 12.6 can be used satisfactorily for the design of the microstrip lines on GaAs substrates. The dielectric loss of semi-insulating GaAs was negligibly small. The transmission line loss, most of which is due to conductor loss, was about 0.22 dB per wavelength at 15 GHz or higher frequencies for a 50-Ω stripline (3-μm thick gold) on a 0.2-mm thick GaAs substrate. This is small enough from a practical point of view.

The developed monolithic amplifier on a 2.75-mm× 1.45-mm chip exhibited the minimum noise figure of 6.2 dB with an associated gain of 7.5 dB at 21-GHz band without any external matching. The bandwidth at 1-dB gain compression was 1.7 GHz. From these results, monolithic amplifiers seem very promising in obtaining a superior performance with a sufficient reproducibility at *K*-band or higher frequencies.

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Frequency Tuning of Microstrip TRAPATT Oscillators

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Abstract—**This paper describes two methods of magnetically tuning the frequency of a microstrip TRAPATT oscillator. Tuning ranges in excess of 100 MHz at a center frequency of 2 GHz have been obtained at peak output power levels of typically 40 W with variations in output power of ±0.2 dB. In one of the methods the harmonics of the oscillator are separated which may enable additional diagnostic information to be obtained for the TRAPATT oscillator.**

I. Introduction

The TRAPATT oscillator is now being evaluated as the transmitter unit in compact, all solid-state pulsed radar sets. If frequency agility is required it becomes necessary to study methods of tuning a TRAPATT oscillator. This paper describes two methods for moderate tuning rates which involve the use of a variable external magnetic field. Since the required field change in each method is relatively small, the rate of change of frequency may be as fast as several tens of megahertz per microsecond. The first method uses the change of the effective permeability of a ferrite substrate created by varying an applied magnetic field to change the electrical length of the triggering section of a microstrip TRAPATT oscillator. The second and preferred method changes the phase of selected harmonics of a microstrip TRAPATT oscillator by varying the ferrimagnetic resonance of a suitably biased and positioned garnet sphere. Both methods of tuning use the same basic TDT (Time Delay Triggered) type of microstrip oscillator already described [1], [2].

II. Tuning by Variation of Effective Permeability

Permeability tuning was first investigated by Glance [3] for the tuning of IMPATT oscillators and later by Liu [4] for TRAPATT oscillators. The oscillator is of the TDT type whose oscillation frequency is determined mainly by the electrical length of the low-impedance triggering line [1]. Since the electrical length is a function of the permittivity and permeability of the substrate material, it follows that the line may be tuned if either of these material parameters can be adjusted. By defining the TRAPATT circuit on a microwave ferrite substrate it is possible to vary the electrical length of the triggering line via the change in the permeability induced by applying a small, variable, magnetic field in the plane of the substrate. The construction of the prototype oscillator is shown in Fig. 1.

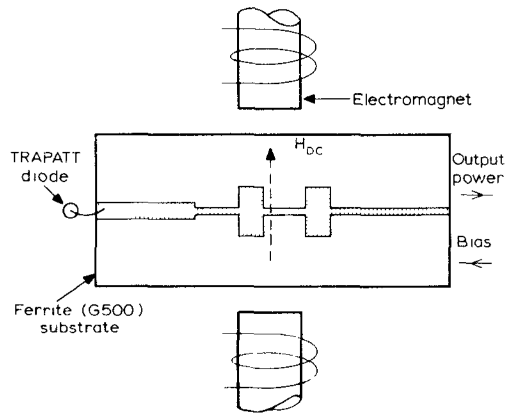

Fig. 1. Schematic of magnetically tuned TRAPATT oscillator.

The results obtained by applying a small magnetic field whose angular direction could be changed perpendicular to the direction of propagation in the microstrip line (see Fig. 1) are given in Fig. 2. The parameter on the graph is the angle between the normal to the magnetic field direction and the plane of the substrate. It can be seen that an optimum tuning range of approximately 60 MHz was obtained from an initial frequency ($H=0$) of 2.19 GHz. The corresponding power versus field variation is shown in Fig. 3. The output power remained substantially flat (13 W peak ±0.5 dB) over this frequency range and the

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