GaAs MESFET Small-Signal *X*-Band Amplifiers

NICHOLAS A. SLAYMAKER, R. A. SOARES, AND JAMES A. TURNER

***Abstract*—This paper describes several techniques used to design and realize small-signal amplifiers at *X* band using Plessey 1-μm gate-length GaAs MESFET's.**

Noise figures of 3 dB or better at 8 GHz with associated gains of 5.5 dB have been produced. The mounting of GaAs MESFET's on 25-mil-thick alumina substrates and their *S*-parameter characterization is described. Owing to some uncertainties in these measurements, four parallel approaches were used to realize amplifiers. The "designed," "semidesigned," "semituned," and "tuned" methods are described and results are presented for each case. A semidesigned single-stage amplifier has a gain of 8 ± 0.6 dB from 8.5 to 9.5 GHz and a minimum noise figure of 4.4 dB. A semituned amplifier can be tuned from 8 to 10 GHz with VSWR's less than 2:1 over any 600-MHz bandwidth in that range.

I. Introduction

THE GaAs MESFET, the first three-terminal device capable of operating effectively at *X*-band frequencies, is now a mature device. Transistors with a 4-μm gate length have been integrated in an ESRO TD satellite. One-micron gate-length devices have been used in a 12-GHz amplifier for the Communications Technology Satellite [1]. GaAs MESFET preamplifiers are being considered for the proposed German 12-GHz television system. An 11-GHz amplifier using 1-μm gate-length transistors has been evaluated [2] for use in the next generation single-conversion satellites. Amplifier results at *Ku* band have been presented [3]. At *C*-band frequencies and below, the GaAs MESFET faces competition from silicon bipolar transistors, but at higher frequencies it offers clear advantages. At *X*-band frequencies its range of application is very wide; it can be used in oscillators [4] with efficiencies and power outputs suitable for local-oscillator applications, in mixers [5], with the future possibility of an *X*-band receiver using only GaAs MESFET's. Power GaAs MESFET's are already showing promise at high frequencies [6]–[9] and a medium power device has been shown to be a very suitable 1-Gbit/s modulator for a DH-GaAlAs laser [10], [11]. The single- and dual-gate [12] MESFET will be very important in gigabit per second logic [13].

In this paper, we shall discuss GaAs MESFET small-signal amplifiers, with particular reference to their design and realization at *X*-band frequencies.

II. Device Fabrication and Performance

The GaAs MESFET's used in the amplifier, oscillator, and modulator work referenced in this paper were produced in epitaxial material incorporating a buffer layer. This was

Manuscript received October 2, 1975; revised December 24, 1975. Part of this work was carried out with the support of the Procurement Executive, Ministry of Defence, sponsored by D.C.V.D. This paper is published by the kind permission of the Directors of the Plessey Company Ltd.
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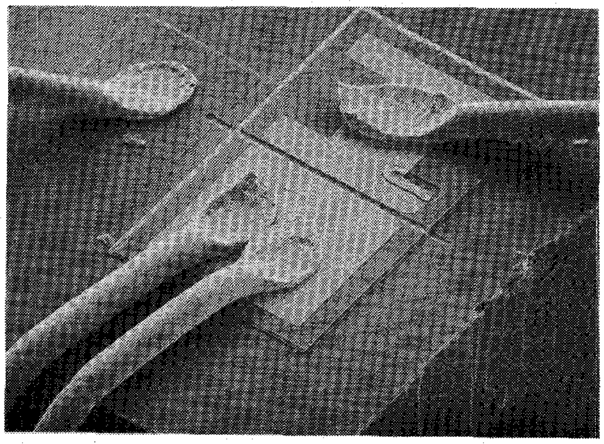


Fig. 1. Microphotograph of *X*-band MESFET.

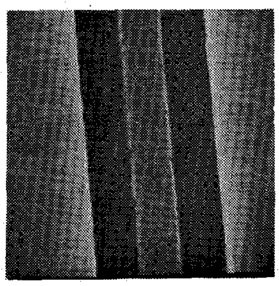
grown by vapor phase epitaxy as developed in the authors' laboratories [14]. The use of a high-resistivity buffer layer grown between the relatively impure, chromium doped, semi-insulating substrate material and the thin active n-type layer considerably improves the electrical properties of the epitaxial layer [15]. The buffer layer restricts diffusion of impurities from the substrate and gives near theoretical electron mobilities at the all-important interface region between the active layer and the buffer layer.

The *X*-band GaAs MESFET's used in this work had gates defined by electron-beam lithography. The source, drain, and gate metallization patterns were all defined by the now standard "float-off" process. The aluminum gate electrode is nominally 1 μm long. The complete device is shown in Fig. 1. Measured noise figures for this device are 4.5 dB at 12 GHz with an associated gain of 6 dB.

Improvements in mask making and in device processing techniques now enable conventional photolithography to be used to produce 1-μm gate-length transistors with comparable line definition to those fabricated by electron-beam lithography. The microphotographs in Fig. 2 show that the definition of a photolithographic gate stripe compares well with one made using an electron beam. The real advantages of the electron-beam approach are that its ultimate line resolution (linewidths of 0.2 μm can be produced) and the accuracy with which successive process steps can be aligned is far superior to any optical technique. Recent improvements in material and device technology have resulted in devices with improved noise figures and gains. The best laboratory result at 8 GHz is a noise figure of 2.2 dB with an associated gain of 5.5 dB for a photolithographic 1-μm gate-length transistor.

A typical Plessey 1-μm gate-length GaAs MESFET has a drain saturation current, I_{dss}, of 30 mA. Devices used for microwave-amplifier design are operated at 5-V drain-to-

(a)



(b)

Fig. 2. SEM microphotographs of 1-μm-long gates defined by (a) electron beam and (b) photolithography.

source bias and have a transconductance, g_m, of 10 mS and a gate pinch-off voltage of -4 V at 10-μA drain current.

If the GaAs MESFET is to be accepted for use in any microwave system, its reliability must be beyond question. Work both in temperature stress testing under full dc bias and long-term room-temperature operation has shown that the GaAs MESFET is indeed a very reliable device. The step-stress test results give an Arrhenius predicted mean time to failure (MTTF) in excess of 10^7 h at a junction temperature of 70°C. The results of the room-temperature test reinforce this result, for to date half a million device hours have been accumulated with no device failures.

Resistance to RF burn-out is also important in some GaAs MESFET radar preamplifiers. Experiments have shown that negligible degradation in performance is observed when well-matched X-band amplifiers are subjected to input CW powers of up to 100 mW. A nonreflective limiter has been used with the X-band amplifiers described in Section IV. This unit limits RF peak powers of 100 W to less than 50 mW. The fact that the GaAs MESFET will withstand CW input powers of at least twice this value indicates that a protected amplifier can be used with complete confidence in the majority of front-end applications.

III. MESFET Amplifiers with Center Frequencies Below X Band

At frequencies below X band, packaged devices do not give a seriously inferior performance to bare chip devices. Thus convenient Leadless Inverted Device (LID) or stripline packages can be used, and the transistor may be accurately characterized by measurement of its S-parameters using a manual network analyzer in the normal way. Two-micron gate-length devices in LID packages are unconditionally stable at frequencies above 2 GHz.

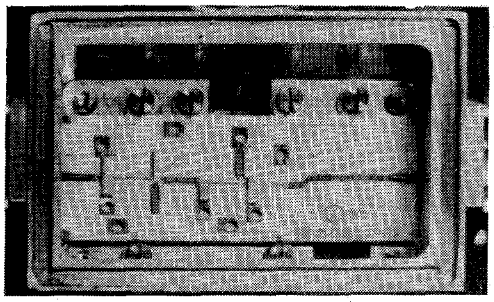


Fig. 3. Three-stage, 5.00–5.25-GHz MESFET amplifier.

Narrow-band, 10 percent or less, amplifiers can be efficiently designed by letting a microwave CAD program, e.g., COMPACT [16], optimize an initial, single-frequency, Smith chart design. Fig. 3 shows a three-stage C-band amplifier designed for a flat gain response in the microwave landing system frequency band. A cascade of two such single-ended amplifiers had a gain of 18 $\pm$ 0.25 dB from 5.00 to 5.25 GHz, input and output VSWR's less than 1.25:1, and a noise figure of 7 dB at 5 GHz. A two-stage S-band amplifier has a 2.4-dB noise figure and a gain of 17 dB from 2.9 to 3.2 GHz (-1-dB bandwidth). Both these amplifiers use 2-μm gate-length devices mounted in LID packages. Short shunt stubs were used in both of these amplifiers to ensure that gain out-of-band was less than that in-band, and to introduce dc bias.

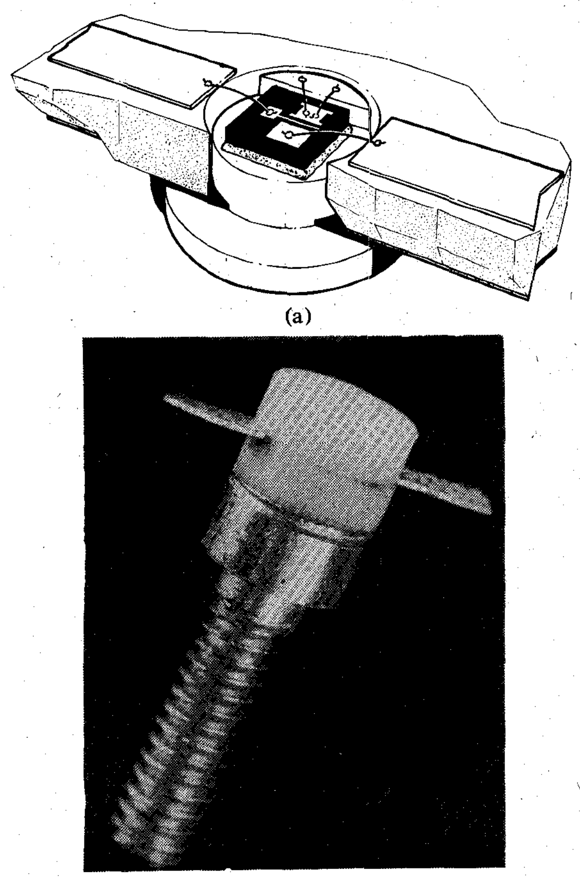
IV. X-Band Amplifier Design and Performance

Using a manual network analyzer and simple calibration techniques, it is difficult to measure the S-parameters of a microstrip mounted GaAs MESFET to the accuracy necessary for amplifier design at X-band frequencies. Errors are also introduced into microstrip circuit designs by the parasitics which are associated with various microstrip discontinuities. Although recent publications on this topic [17], [18] have proved helpful, they do not cover the wide variety of discontinuities encountered in practical amplifier designs.

It is therefore rarely possible to realize an amplifier which performs exactly as designed. For this reason the authors have adopted four separate approaches to amplifier design. These approaches, labeled designed, semi-designed, semi-tuned, and tuned, will be described in this section and results will be presented for amplifiers realized by each of these techniques. None of these approaches is new but the authors wish to show how these techniques, which have been used by microwave engineers for some time, can be applied to the specific problem of producing GaAs MESFET X-band amplifiers.

A. Device Mounting

The mounting of the GaAs MESFET in a 25-mil-thick alumina microstrip circuit at X band can prove a difficult problem. Conventional packages such as the LID have parasitic reactances which seriously degrade the gain and bandwidth in X band. However, two low parasitic systems successfully used by the authors are the chip on disk (COD) and the microstrip package (P103) shown in Fig. 4. The



(a)

(b)

Fig. 4. X-band microstrip mounts. (a) Chip on disk. (b) P103.

TABLE I
S-PARAMETERS OF A TYPICAL PLESSEY COD MOUNTED 1-μm GATE-LENGTH GaAs MESFET

Frequency GHz	S_{11}		S_{12}		S_{21}		S_{22}	
	Magnitude	Angle, deg.	Magnitude	Angle, deg.	Magnitude	Angle, deg.	Magnitude	Angle, deg.
8.0	0.62	-64	0.066	134	1.19	150	0.88	-30
9.0	0.46	-87	0.089	129	1.34	140	0.84	-43
10.0	0.41	-96	0.082	138	1.22	130	0.82	-38
11.0	0.40	-116	0.082	138	1.09	125	0.83	-45
12.0	0.25	-107	0.087	154	1.11	129	0.86	-42

flange of the COD mount is soldered or epoxy bonded to the microstrip ground plane. The ledge on the post ensures that the source-to-ground bond is kept as short as possible and that it is repeatable from device to device. It is sometimes necessary to increase the common source lead inductance, and then a COD without a ledge can be used. The P103 is a hermetic package, 2-mm outside diameter, which has been used both in narrow-band amplifiers and in oscillators [1], [19].

The Plessey 1-μm gate-length MESFET's used in the X-band amplifiers described in this paper were fabricated using electron-beam lithography. Typical COD mounted devices have a maximum available gain (MAG) of 10 dB and a minimum noise figure ($F_{\min}$) of 3.5 dB at 8 GHz. The corresponding figures for a device mounted in a P103 package are a MAG of 8 dB and a $F_{\min}$ of 4 dB. Thus the convenience and mechanical robustness of a packaged transistor are paid for by a slight degradation in achievable performance. By including impedance-matching networks on the GaAs MESFET chip [26] or in the transistor package, the superior electrical performance of a COD mount may be achieved with a packaged device. This approach is currently being investigated by the authors.

B. Device Characterization

Table I gives the S-parameters of a Plessey 1-μm gate-length MESFET, produced by electron-beam lithography. It was COD mounted in a 1-in-square alumina substrate which was 25 mil thick and included a reference through line and two microstrip open circuits. These open circuits were used to set the reference plane of the manual network analyzer used at the beginning of the bond wires leading to the transistor. Later sections in this paper describe how amplifiers have been produced using data obtained with this simple measurement procedure. It is shown there how quite reasonable agreement between the computed and measured performances is obtained.

More accurate measurement of two-port S-parameters at any frequency require further calibration measurements. The authors have had some success with a system using microstrip short circuits, off-set short circuits, open circuits, and matched loads but the standards need to be made very precisely and their accuracy degrades rapidly with each reconnection.

The authors favor an alternative procedure in which the MESFET, mounted in a 50-Ω microstrip line is connected to an automatic network analyzer via high-quality APC-7-to-microstrip adapters. Full two-port correction is then applied in the normal way, using precision coaxial standards, and the transistor fixture, including adapters, is accurately measured as a two-port network. The measurement plane is then moved from the APC-7 plane to the transistor reference plane by "subtracting" the effects of the adapters and the microstrip lines with a computer program.

The adapters, type OS14493A, are characterized as described in [20]. At frequencies around 10 GHz, the equivalent series inductance is 0.080 nH and the equivalent shunt capacitance 0.025 pF. Their length from the APC-7 plane to the microstrip plane is equivalent to a 39.5-mm air line, which is taken to be lossless. The only other corrections made are for the loss and dispersion in the microstrip line.

The effect of this correction is mainly seen in the reflection coefficients although $|S_{21}|$ is slightly increased. If no correction for the adapter parasitics is made, errors of 10° in $\angle S_{11}$ and $\angle S_{22}$ can result. The correction makes $\angle S_{11}$ and $\angle S_{22}$ monotonic and causes S_{11} and S_{22} to fall more nearly on constant resistance and constant conductance circles, respectively. Gains computed from the two sets of S-parameters agree very closely.

This error correction procedure does not, however, take account of stray coupling between the input and output ports of the transistor fixture. Fig. 5 shows the variation in transmission loss obtained across X band for a COD mount in a simple, open 1-in × 1-in alumina substrate. This poor isolation will considerably modify the measured S-parameters; for example, the measured value of $|S_{12}|$ can be increased by more than 40 percent. Enclosing the fixture in a waveguide that is cutoff below 15 GHz improves the transmission loss to 50 dB, which means that it contributes less than 4-percent error to $|S_{12}|$ measurements. A similar transmission loss may also be obtained in an open fixture by reducing the thickness of the substrate from 25 to 10 mil, but the penalty is that high-impedance lines cannot be produced so easily. Also shown in Fig. 5 is the very low transmission loss of an empty LID package in a transistor fixture.

C. Designed Approach

In order to realize reasonably broad-band gain in X band, it is necessary to obtain a good starting point, and subsequently refine the circuit performance with an optimization program. A good account of the theory of filter synthesis leading to such a starting point has been given by Liechti [21]. Considering first input matching, the authors have found that a $\lambda/2$ resonator, coupled by only impedance inverters to the resonated FET gate, can provide a good broad-band match to their transistors. Thus the series interdigital capacitor which forms part of the admittance inverter in [21] is not necessary, which makes the circuit easier to realize on a 25-mil-thick alumina substrate. DC isolation can be achieved by low-loss, printable, dc blocks [22] or by small 25-pF monolithic capacitors. Fig. 6 shows the measured input VSWR of such a circuit made according to the results of a theoretical 9.5–10.5-GHz design (no computer optimization). The inset shows how the impedance inverters are approximated by shunt inductors of 1.3 and 2.7 nH, which, in turn, are approximated by shorted lengths of high-impedance transmission lines. These lines are realized by laying 1-mil-diam gold bond wires on the surface of the alumina substrate. COD-type posts, whose tops are flush with the substrate, are used to form good short circuits. A COD-mounted chip device is used. A good agreement with the computed performance is seen, although a very simple straightforward measurement method was used with no correction for the VSWR of the launcher.

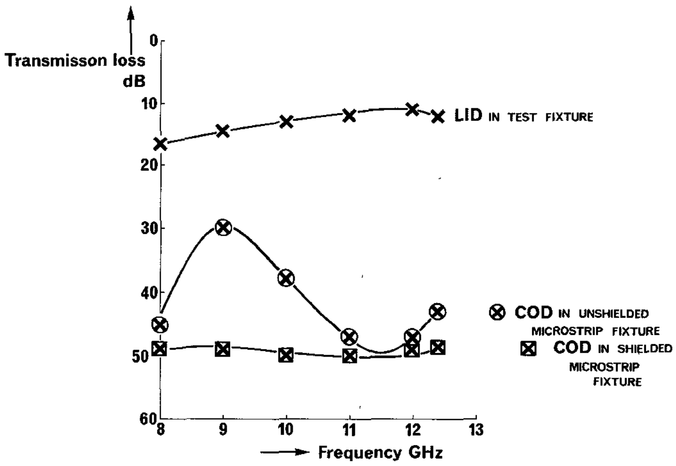


Fig. 5. Transmission loss of COD and LID packages.

To match the output, the first element should approximate a lumped inductor as closely as possible to resonate the transistor's output capacitance. A high-impedance transmission line, of about 300 Ω, was realized as shown in Fig. 7 by stretching a 1-mil-diam gold bond wire over a 20-mil-deep slot milled in the 25-mil-thick substrate. A simple $\lambda/4$ transformer completes the circuit which gives the measured results shown.

Combining these two matching techniques to form a complete amplifier module widens the gap between the measured and computed performances. However, this module will form a good starting point for a subsequent semidesign exercise.

D. Semidesigned Approach

This technique involves the use of an amplifier designed by filter synthesis or Smith chart matching techniques as a

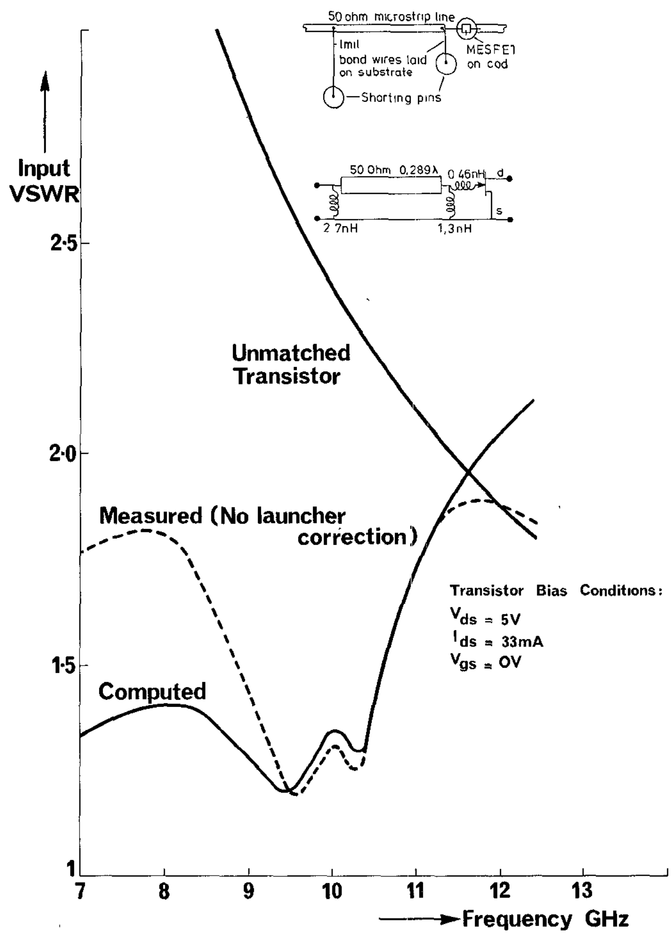


Fig. 6. Input matching of a GaAs MESFET.

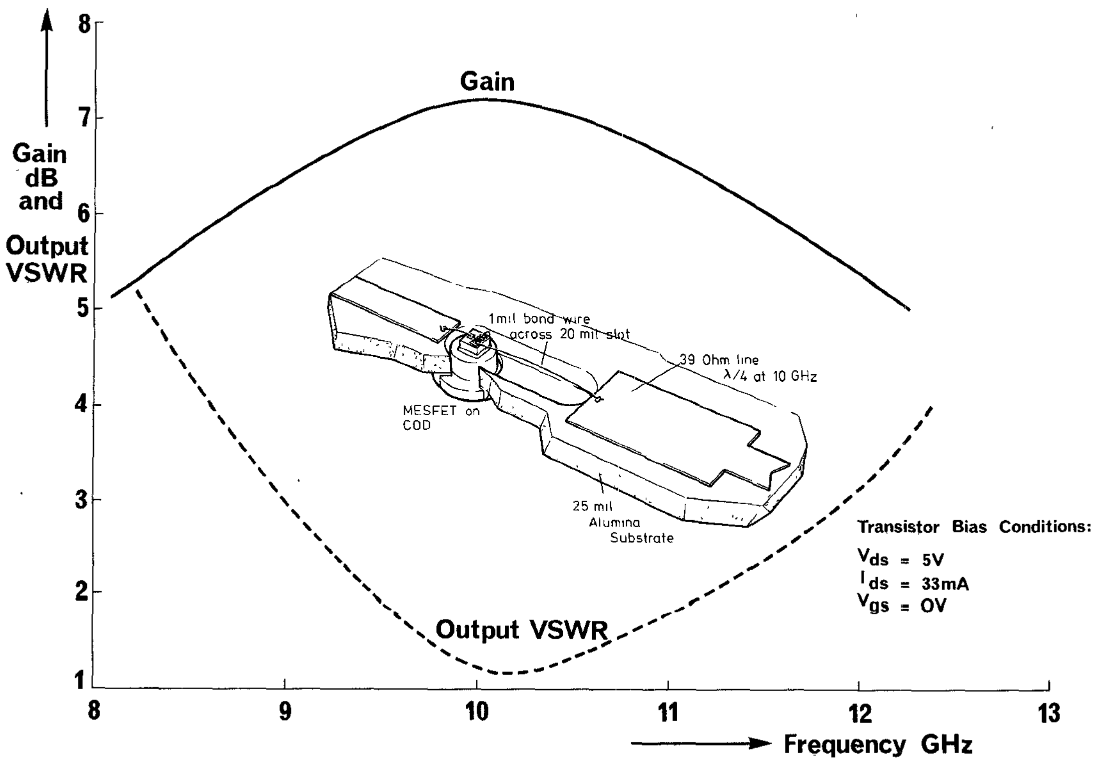


Fig. 7. Output matching of a GaAs MESFET.

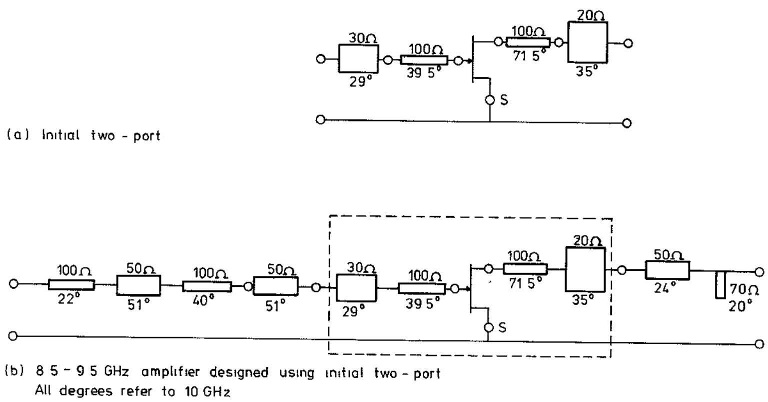


Fig. 8. Example of a semidesigned amplifier.

TABLE II
THEORETICAL AND MEASURED PERFORMANCE OF THE SEMIDESIGNED AMPLIFIER MODULE SHOWN IN FIG. 8(a)

Frequency GHz	THEORETICAL PERFORMANCE			MEASURED PERFORMANCE		
	Gain, dB	Input VSWR	Output VSWR	Gain, dB	Input VSWR	Output VSWR
8.0	6.5	3.1	7.7	5.3	2.2	9.0
9.0	9.6	2.3	2.4	8.2	2.1	2.0
10.0	7.8	1.9	2.2	6.0	3.1	2.2
11.0	2.6	3.3	9.0	2.0	3.4	3.8

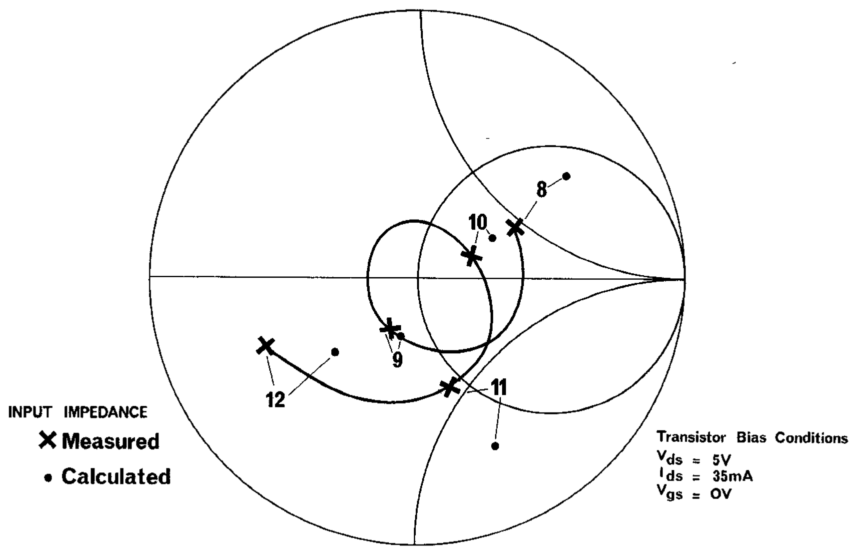


Fig. 9. Semidesigned amplifier input match.

starting point. Often the circuit chosen does not perform entirely as predicted because of errors in transistor characterization and the inaccurate modeling of various microstrip discontinuities. However, since this new two-port network is partially matched, it can be measured with greater accuracy than the unmatched transistor, and extra circuit elements can then be added to enable it to meet the required specification. This technique is extremely flexible, provided that the initial matching elements are judiciously selected. A partially matched unit amplifier has been used by the authors as the basis of both narrow- and wide-band amplifier designs.

An example of the application of the semidesign amplifier technique is shown in Fig. 8. A preliminary amplifier unit, Fig. 8(a), was first designed by adding matching elements to a COD-mounted transistor with the S-parameters given in Table I. This basic amplifier, designed using Smith chart matching techniques as described by Froehner [23] makes use of a high-impedance line followed by a low-impedance section for both input and output matching. The results, theoretical and measured, obtained for this module are given in Table II. It should be noted that no allowance has been made for the effects of junction discontinuities or microstrip-line losses in the theoretical data presented in Table II. The two-port S-parameters of the unit amplifier were carefully measured and used to design the 8.5–9.5-GHz amplifier shown in Fig. 8(b).

A single-stage amplifier was constructed to the design of

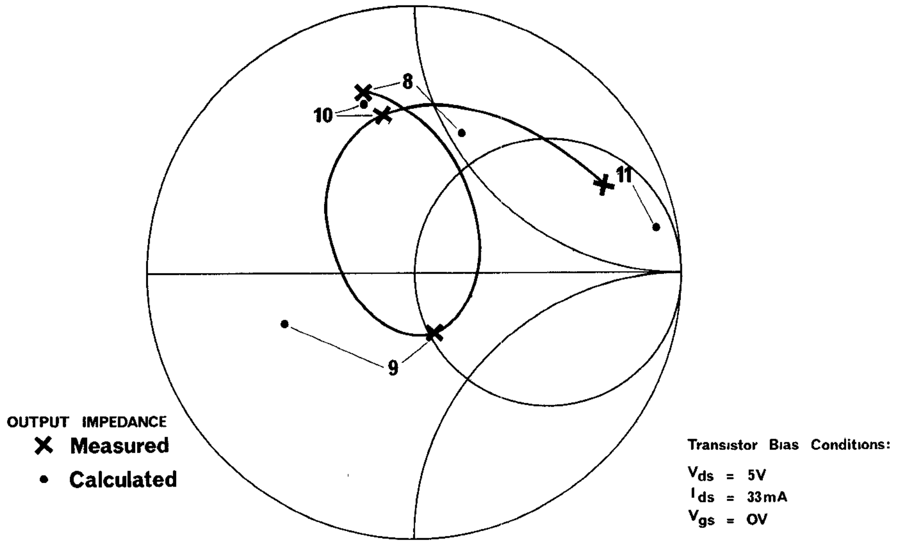


Fig. 10. Semidesigned amplifier output match.

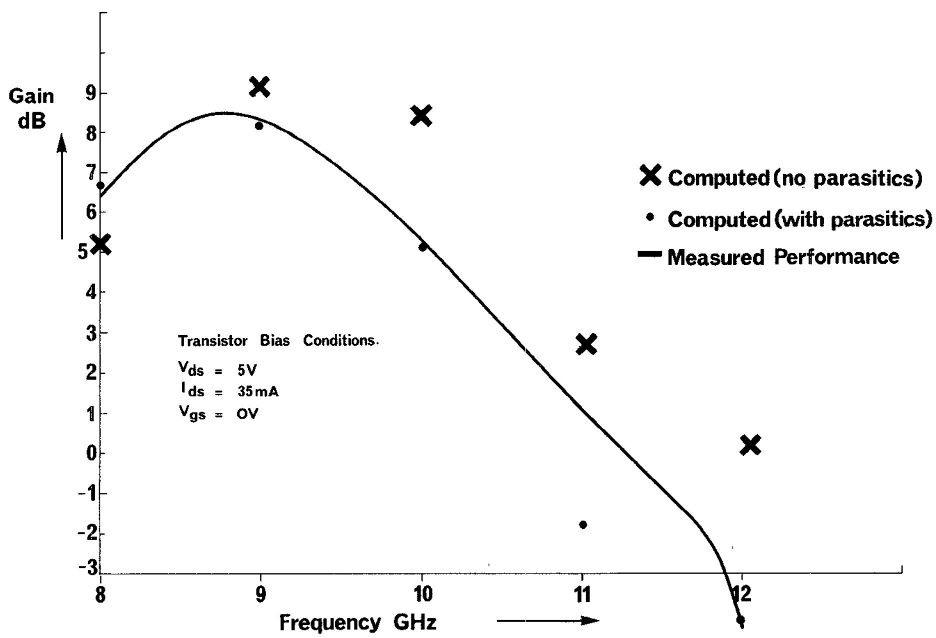


Fig. 11. Semidesigned amplifier gain.

Fig. 8(b), using a Plessey 1-μm-gate GaAs MESFET under the following bias conditions: $V_{ds} = 5$ V, $I_{ds} = 18$ mA, and $V_{gs} = 0$ V. It gave the performance shown in Figs. 9–11; the gain response was 8 dB $\pm$ 0.6 dB and the input and output VSWR's <2.5:1, over the frequency range 8.5–9.5 GHz. The noise figure of this amplifier was measured at 9.5 GHz for different gate and drain voltages and the results are summarized in Table III. The minimum noise figure of the amplifier was 4.4 dB with an associated gain of 3.1 dB; alternatively, an amplifier gain of 5.8 dB with a noise figure of 4.7 dB could be achieved. If the computed loss of the input microstrip matching network is allowed for, a minimum-device noise figure of 4.1 dB at 9.5 GHz is indicated.

Fig. 11 also shows the predicted performance of the amplifier with and without the effects of parasitics at the microstrip discontinuities. At a step change in width the parasitics are a series inductance and a shunt capacitance.

TABLE III
GAIN AND NOISE FIGURE 9.5–10.5-GHz AMPLIFIER UNDER VARIOUS BIAS CONDITIONS, MEASURED AT 9.5 GHz

Gain dB	Noise Figure dB	Bias Conditions		
		V_{ds}, V	I_{ds}, mA	V_g, V
8.0	5.4	5.0	18.0	0.0
7.1	5.3	2.5	17.5	0.0
5.8	4.7	2.0	14.0	-0.3
3.1	4.4	1.5	9.5	-0.7

The inductance was calculated as suggested by Wight *et al.* [20] and the capacitance was approximated as the difference in the end-effect values [24] of the two lines involved. The T-junction was specified in the manner described in [18]. It can be seen that good agreement with the measured performance is obtained when these parasitics are included. The discrepancy at 11 GHz is thought to be due to errors in

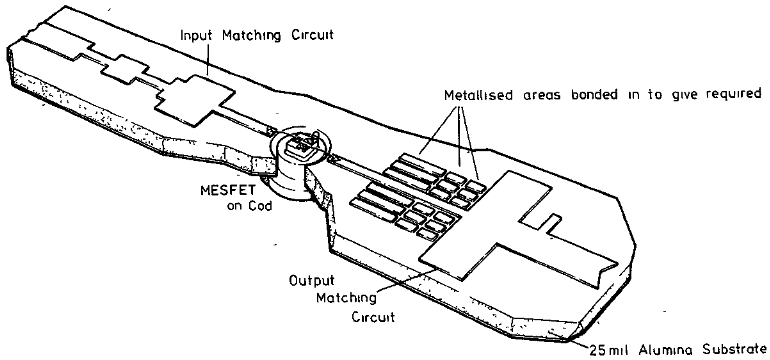


Fig. 12. Semituned X-band amplifier layout.

the S-parameter data, which were derived in the simple way described in the beginning of Section IV-B.

Two further extensions to the semidesign method can be made using a well-characterized circuit, such as that of Fig. 8(b), as the starting point. Firstly, by applying a sensitivity analysis to the circuit, the relative effects of the various circuit elements on amplifier response can be adjudged. Then, by selecting one or more relatively independent sensitive elements, the amplifier may be tuned over a useful frequency range. The latter approach is described in greater detail in the section on semituned amplifier design. Secondly, a computer optimization routine can be applied to the semidesigned circuit in order to extend its gain and terminal match over a wider frequency bandwidth, or to improve its performance over the same or adjacent frequency bands. The application of an optimization routine to the amplifier shown in Fig. 8(b) allowed its performance to be extended to provide gain of 5.7 dB $\pm$ 0.5 dB, with input and output VSWR's $<3:1$, over the frequency range 8–10.2 GHz.

E. Semituned Amplifier Approach

It is sometimes found that an amplifier, which has been designed in a laboratory is not capable of being commercially produced without some modification to the circuit, to take account of the device and circuit manufacturing tolerances. A further difficulty lies in the measurement of the S-parameters of large numbers of GaAs MESFET chips at X band.

A simple method can be applied to solve these problems. The effect on the amplifier response of devices with the minimum acceptable RF performance is first examined. In narrow-band amplifier designs, the variations in device S-parameters often cause a frequency shift in the gain and VSWR's of the amplifier. Next a sensitivity analysis of the amplifier circuit, with typical transistor S-parameters, is carried out to discover which elements are capable of having a reverse tuning effect on the amplifier performance. By selecting the appropriate circuit elements, it is then possible to correct for the effects of spreads in device S-parameters by adjustment of the sensitive elements' dimensions.

This principle can be extended to adjust the frequency response of an amplifier, regardless of spreads in transistor S-parameters. This "semituned" principle has been applied to design a narrow-band amplifier with a center frequency capable of being tuned from 8 to 10 GHz [25]. The amplifier has an instantaneous -0.5-dB bandwidth and terminal VSWR's less than 2:1 over any 600 MHz in that frequency range, while the gain decreases from 7.5 dB at 8 GHz to 6.5 dB at 10 GHz.

A diagram of the semituned amplifier is shown in Fig. 12. The frequency-sensitive element is the high-impedance line immediately following the transistor in the output matching circuit. The impedance of this line can be varied as required by bonding in the small metallized areas on either side of this line. Two of these amplifiers have been cascaded to give an overall gain of 12.5 dB and noise figure of 6.0 dB at 9 GHz.

F. Tuned Approach

This technique consists of mounting a device in a COD or P103 package on a microstrip substrate with 50-Ω lines and bias filters on the input and output ports [2]. Input and output tuning over a wide range of frequencies can be achieved by sliding 3-mm-diam metal disks along the 50-Ω lines. Using this method of tuning, an amplifier with 42-dB gain at 11.2 GHz and with a -1-dB bandwidth of 260 MHz has been realized. The third-order intermodulation level of this amplifier with two -50-dBm signals applied to its input was -35 dB of its output power. An output power of 8.5 dBm at 1-dB gain compression was obtained. All stages were biased to $V_{ds} = 5.0$ V and $V_{gs} = 0$ V.

The main purpose of this technique is, however, as a diagnostic tool. It allows an amplifier to be quickly assembled to give approximately the performance required. This prototype amplifier can then be used in order to investigate such effects as variation of gain with temperature and the maximum power output obtainable from a small-signal X-band amplifier at its 1-dB gain-compression point. For instance, the 11.2-GHz amplifier quoted gave a gain variation of ± 1.2 dB over a temperature range 7°C to 35°C which was reduced to 1 dB total by applying a temperature-compensated negative bias voltage to the gate of the second transistor. The bias supply consisted of a thermistor controlled p-n-p emitter–follower drawing current through a 400-Ω resistor connected to the transistor gate. As the ambient temperature was increased the negative gate bias was reduced, thereby keeping the overall amplifier gain constant.

V. Conclusions

The GaAs MESFET is a mature, reliable device capable of operating efficiently at X band and higher frequencies. Electron-beam lithographic techniques are available for producing devices with gate lengths well below 1 μm; thus increasing the GaAs MESFETS' useful operating frequency to well above X band.

Materials other than GaAs are being considered, the foremost of which is InP. MESFET's in this material are being fabricated and it is expected that, for comparable geometries, their maximum frequency of operation will be about 30 percent higher than for GaAs devices.

High-performance distributed or semidistributed X-band amplifiers are now available. At higher frequencies, it is anticipated that lumped-element, monolithic MESFET amplifiers will be used. Such amplifiers fabricated in GaAs are already showing promise at X-band frequencies [26], and it is only a matter of time before monolithic amplifiers will be available at *Ku* and *Ka* bands based on GaAs and InP MESFET's.

Acknowledgment

The authors are grateful for contributions from their colleagues at the Allen Clark Research Centre. In particular they would like to thank Dr. S. C. Cripps, who designed the S-band amplifier, for his help with X-band measurements, J. A. Angus, who designed the C-band amplifier while at the Roke Manor Laboratories of the Plessey Company, and H. E. G. Luxton, who was responsible for the tuned-amplifier approach described in this paper. Dr. R. S. Butlin, H. E. G. Luxton, and Dr. S. C. Cripps supplied the latest noise figure results.

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