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A Low-Noise Gallium Arsenide Field Effect Transistor Amplifier for 4 GHz Radio

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A low-noise amplifier for 4 GHz radio has been designed and is in manufacture. The noise figure is ⩽2 dB and the gain is typically 10 dB. Input and output return losses are ⩾25 dB. The insertion loss with failure of either the power supply or the low-noise transistor is typically 5 to 8 dB. The amplifier uses a single gallium arsenide field effect transistor in conjunction with a passive failsafe by-pass network utilizing circulators. This approach permits the noise figure and the gain flatness to be optimized for each amplifier without compromising the input and output matches. It is concluded that this single-transistor amplifier design has significant advantages both in performance and in simplicity over the balanced amplifier design.

I. INTRODUCTION

Gallium arsenide Field Effect Transistors (GaAs FETs) are effecting a revolution in both the design philosophy and the performance capability of new microwave systems. In addition, these devices can often provide an economical means for significantly upgrading the performance of existing systems. Such is the case with the 4 GHz radio system, where an RF preamplifier with a maximum noise figure of 2 dB is achieved with GaAs FETs. In this application, each common multichannel amplifier permits the output power of typically five transmitters to be dropped 4 dB, from 5 watts to 2 watts, while still maintaining the system thermal noise objective for 1500 channels. This significantly increases the life of the transmitter amplifier triodes, thus improving the overall system reliability.

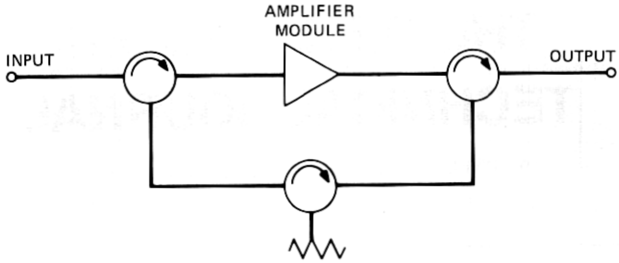

Fig. 1—Single-ended amplifier with provision for unpowered transmission.

II. GENERAL DESIGN CONSIDERATIONS

The use of the GaAs FET amplifier as an RF preamplifier for FM systems requires low intermodulation as well as a low noise figure. In addition, since the amplifier is common to several channels (including the protection channel), reliability is of utmost importance. The two most serious failure mechanisms envisioned are: (*i*) transistor failure and (*ii*) power supply failure. With either type of failure, the GaAs FET amplifier inherently exhibits an unacceptable transmission loss (>20 dB) for radio applications. Use of a balanced amplifier with two transistors coupled with input and output 3 dB hybrid couplers would reduce the gain by only 6 dB for failure of a single transistor. But this redundancy and extra cost gives no relief for loss of the dc supply voltage for the transistors.

Schemes, without active devices, for reducing the loss to <10 dB for either type of failure and which apply to the balanced as well as the single-ended amplifier are shown schematically in Fig. 1 and 2. The signal reflected from the unpowered FETs is fed to the output by interconnecting the normally terminated arms of the coupler (Fig. 2) or isolator (Fig. 1). We have designed, constructed, and evaluated both balanced and single-ended amplifiers.

The requirements for this application are shown in Table I. The choice of the design approach to meet these requirements was based on a de-

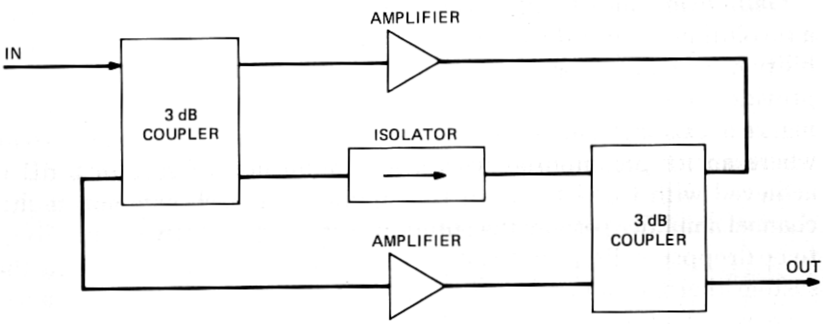

Fig. 2—Balanced amplifier with provision for unpowered transmission.

Table I — Electrical requirements for 3.7 GHz to 4.2 GHz amplifier

	Max.	Min.	Units
Input return loss	—	25	dB
Output return loss	—	25	dB
Noise figure	2.0	—	dB
Gain	11.0	8.0	dB
Gain flatness	±0.5	—	dB
Intermodulation (2A-B intercept)	—	23	dBm
Unpowered insertion loss	10	—	dB

Table II — Single-ended versus balanced amplifier

	Single	Balanced
Gain	Same (8–11 dB)	
Unpowered loss	Same	
Output return loss	⩾25 dB	⩾20 dB
Input return loss	⩾25 dB	⩾17 dB
Transistor failure	6–8 dB loss	2–5 dB gain
Intermodulation (2A-B intercept)		3 dB advantage
Noise figure	0.3 dB advantage	
Transistors required	1	2
Couplers required	0	2
Circulators required	3	1

tailed comparison of the capabilities of the two amplifiers. Based on our laboratory experience, Table II compares the performances that we consider practical in manufacture. We realized that meeting the intermodulation and failsafe requirements with a single transistor would allow significant cost savings. The single-ended GaAs FET amplifier reported here not only meets these requirements but also has match and noise figure advantages. This results from the low loss input circulator which allows us to independently optimize the input circuit match and the transistor source impedance for minimum noise.

III. AMPLIFIER MODULE

The GaAs FET is mounted in a microstrip circuit (Fig. 3). This transmission line permits easy mounting of the transistor and MOS dc-blocking capacitors. The amplifier module per se has no adjustments. Tuning screws near the input and output of the module and in the circulator arms are used to adjust the amplifier for optimum noise figure and gain flatness. This feature compensates for variations in transistor parameters as well as for manufacturing tolerances of the piece parts.

3.1 The GaAs FET output circuit design

In a first order approximation the output circuit elements were determined using BAMP.* Supplying the S-parameters and the input re-

* Basic Analysis and Mapping Program.

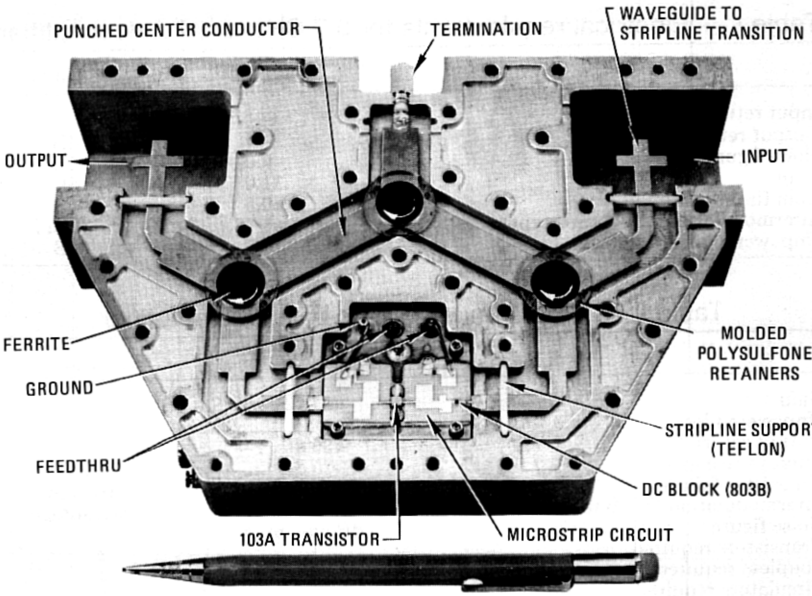

Fig. 3—4 GHz MIC amplifier (open).

flection coefficient (Γ_{MNF}) that results in a minimum noise figure, circles of constant gain are drawn (Fig. 4). If the output circuit reflection coefficient equals Γ_{ML}, optimum gain is obtained. Any deviation from Γ_{ML} results in a loss of gain corresponding to the values indicated on the circles of Fig. 4. Strictly speaking, the set of circles is only valid for one frequency (in our specific case 4 GHz), and a corresponding set would have to be drawn for each frequency under consideration. Since the S-parameter variation over the 12.5 percent frequency band of interest is smooth and relatively small, one set of circles suffices to demonstrate that the output impedance, shown in a dashed line, is reasonably close to match. The actual circuit which produced the impedance was trimmed empirically for bandwidth and flatness of gain.

3.2 The input circuit

The theory of noisy four poles has been treated extensively in the literature.[1–5] It essentially says that the noise figure of the four pole depends solely on the impedance of the input circuit. The noisy four pole is completely characterized by the S-, Y-, or Z-parameters, the source reflection coefficient (Γ_{MNF}) at which the noise figure is minimum (NF_{MIN}), and the equivalent noise resistance (R_n). The measurement of R_n is somewhat cumbersome and is described in Ref. 1. Once the parameters are known, circles of constant noise figure[4,5] can be drawn (Fig.

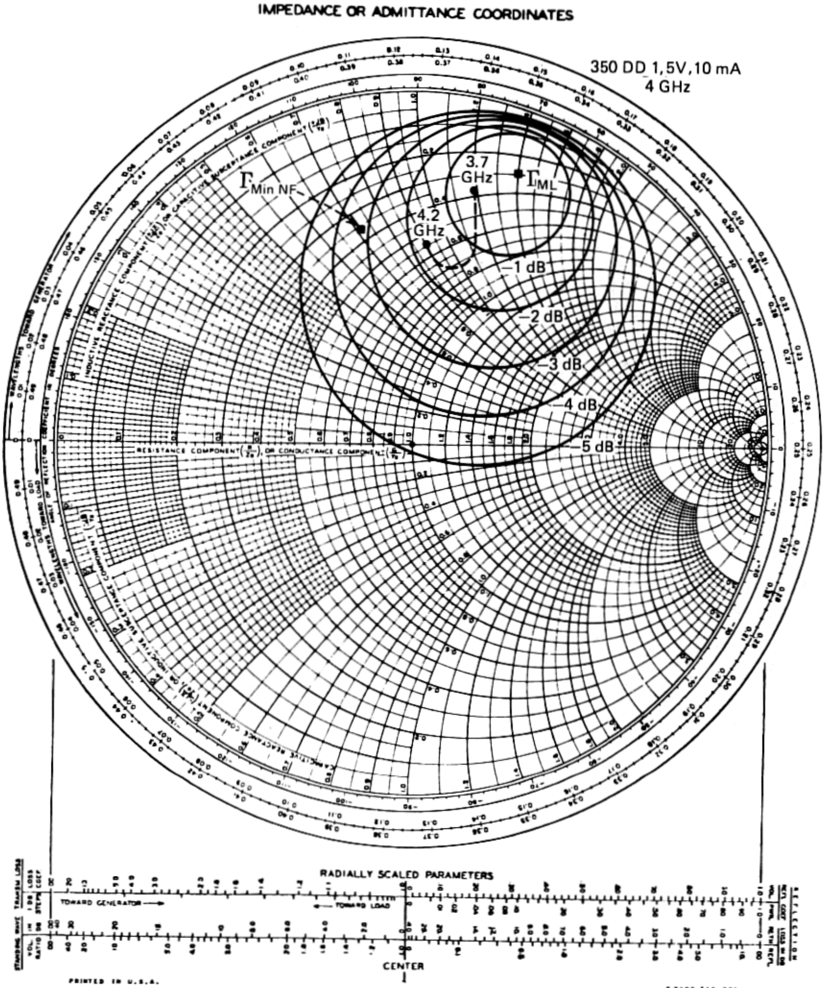

Fig. 4—Circles of constant gain with input tuned for minimum noise figure.

5, solid circles). This set of circles is very insensitive to frequency and independent of the load impedance. The spread of the circles increases with increasing R_n. In our specific case $R_n = 14\ \Omega$. Γ_{ML}, the maximum gain load impedance, has been explained in the output circuit design. The reflection coefficient, Γ_{MS}, in Fig. 5 represents the reflection coefficient of the source that would yield maximum gain, which in our case is about 15.5 dB. It is quite obvious that the points for optimum noise figure and optimum gain are significantly apart. A set of circles similar to the ones in Fig. 4 can be constructed around Γ_{MS}, assuming that the load reflection coefficient is Γ_{ML}. To keep Fig. 5 from becoming over-

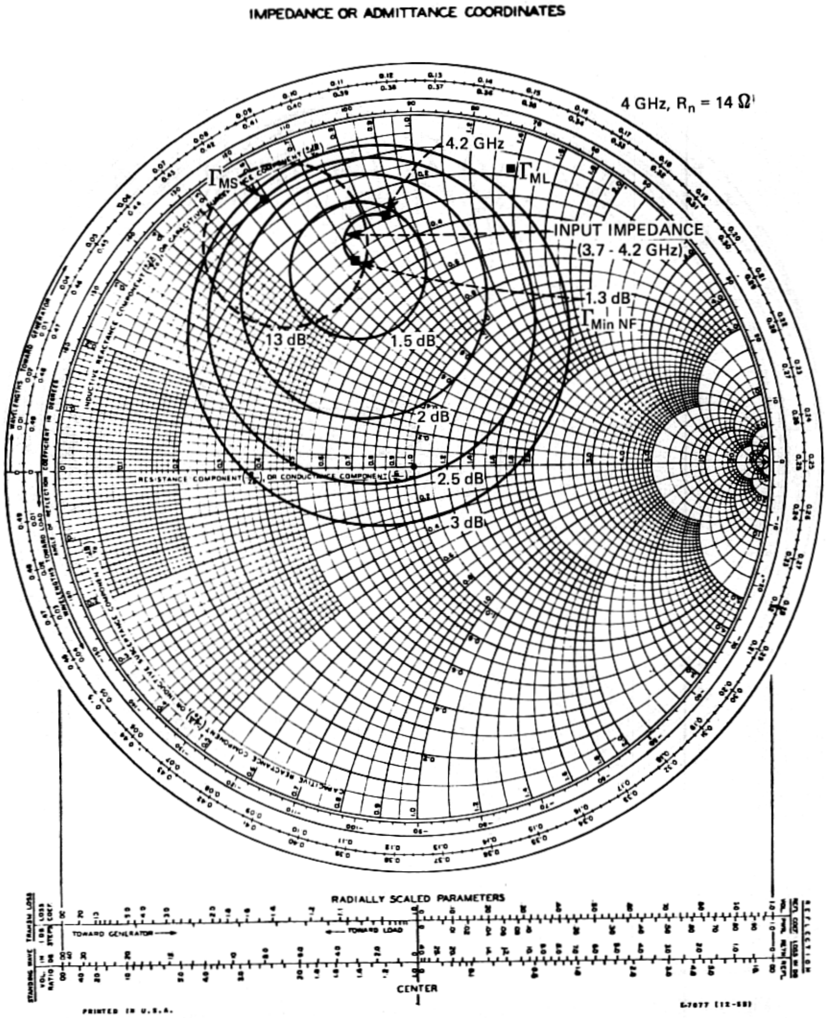

Fig. 5—Circles of constant noise figure.

crowded, only one circle is shown. It is seen that a gain of about 13 dB for optimum noise figure versus 15.5 dB for optimum match can be obtained. This figure, of course, is further reduced by broadbanding and gain flattening, as can be deduced from the source impedance trace in Fig. 5. The performance of the single-ended amplifier module is shown in Fig. 6. The gain of 11.6 dB and corresponding noise figure of 1.5 dB are in good agreement with the values that can be extrapolated from Figs. 4 and 5.

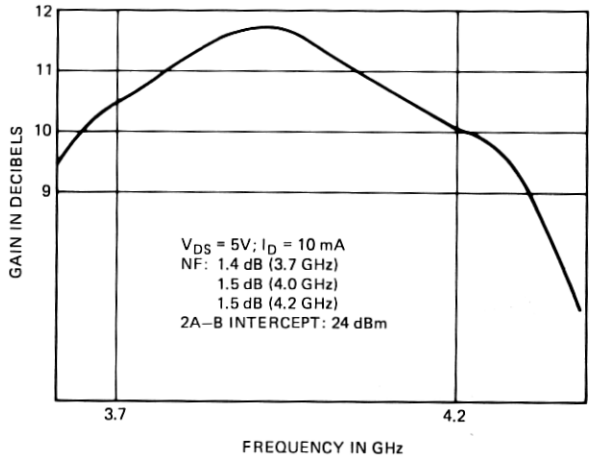

Fig. 6—Performance of amplifier module.

3.3 Final circuit

For the amplifier to be manufacturable, some adjustability is required to compensate for variations in transistor parameters as well as mechanical tolerances on all components. This adjustability is not readily provided in the microstrip circuit, but can be economically introduced in the air dielectric stripline circuit. Pairs of tuning screws are thus located in the air line just in front and just after the microstrip module (Fig. 7). These permit tuning of the amplifier for optimum noise figure and gain flatness.

IV. FAILSAFE BYPASS CIRCUIT

When the GaAs FET is unpowered, both the gate and drain circuits appear approximately as open circuits. The transmission loss typically exceeds 20 dB. If the transistor fails, we expect a short circuit. In either case, the input and output return losses at 4 GHz are typically 2 to 4 decibels.

The provision of three circulators, as shown in Fig. 1, provides an effective passive by-pass circuit. In the normal state, the relatively small reflected input signal is recombined with the amplifier signal at the output of the transistor. This appears as a small ripple on the gain characteristic which can be compensated by output tuning. In the unpowered or failed state, both the gate and drain circuits are "switched" to open or short circuits. The input signal, with relatively small loss, is then directed to the drain circuit of the GaAs FET where it is reflected to the output circulator and directed to the load. The total insertion loss is typically 5 to 8 dB.

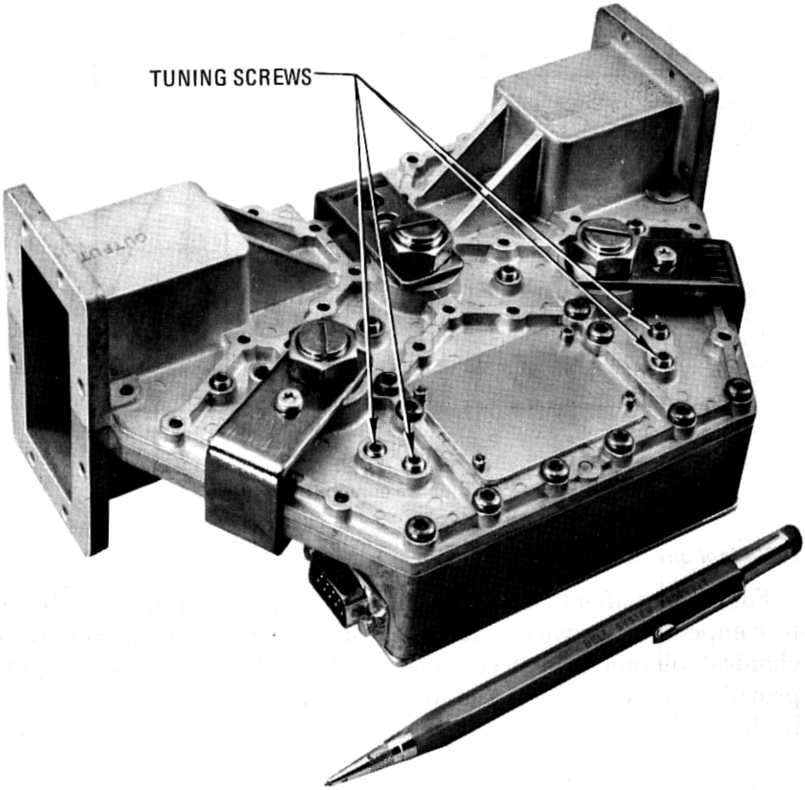

Fig. 7—4 GHz MIC amplifier.

The circulators for the bypass circuit and the waveguide-to-stripline transition[6] were developed in air dielectric stripline (Fig. 8). This simple technology assures minimum circuit losses, low cost parts and assembly, and very high yields. The intermediate circulator is terminated with 50 ohms to provide >25 dB isolation. Since this isolation is only maintained over the 3.7–4.2 GHz band, positive feedback can cause the amplifier to oscillate at lower frequencies. The "low-pass filter" on the output substrate (Fig. 9) eliminated this oscillation which, for our particular by-pass loop, occurred at about 800 MHz.

V. POWER REGULATOR AND ALARM CIRCUIT

The dc operating point for the GaAs FET is a compromise between minimum noise and acceptable linearity. A regulator automatically sets the gate voltage so that $I_D = 15$ mA and $V_{DS} = 4.8$ volts. All GaAs FETs are thus powered identically and require no bias adjustment in manufacture. The amplifier (Fig. 10) operates from a −24 volt supply at 60 milliamperes.

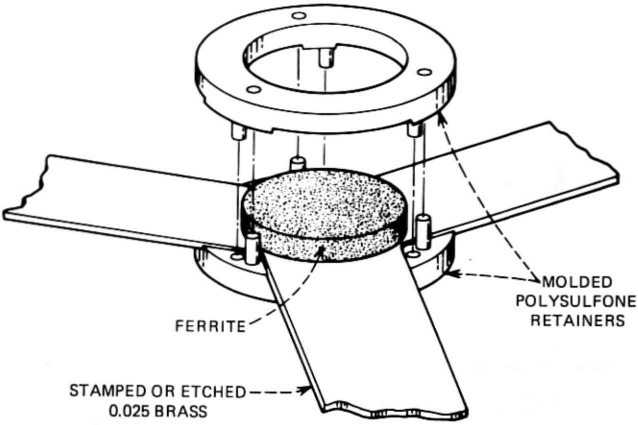

Fig. 8—4 GHz stripline circulator.

In case of transistor or power supply failure ($I_D < 5$ mA or $I_D > 25$ mA), a contact to ground is provided which energizes a remote alarm.

VI. THE LOW-NOISE TRANSISTOR

The GaAs FET was developed at the Murray Hill, New Jersey Laboratory.[7] The gate length and width are 0.8 μm and 2 × 250 μm. The typical noise figure is about 1.2 to 1.4 dB at 4 GHz.

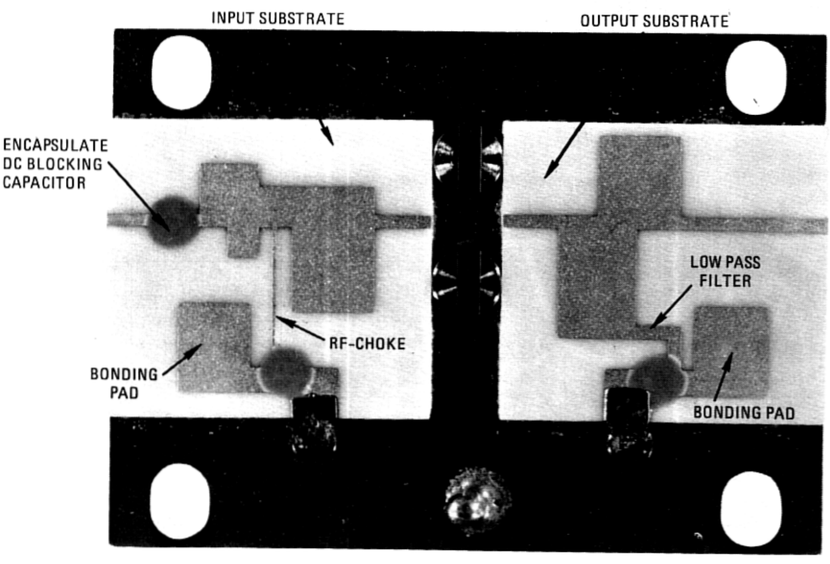

Fig. 9—Amplifier module without transistor.

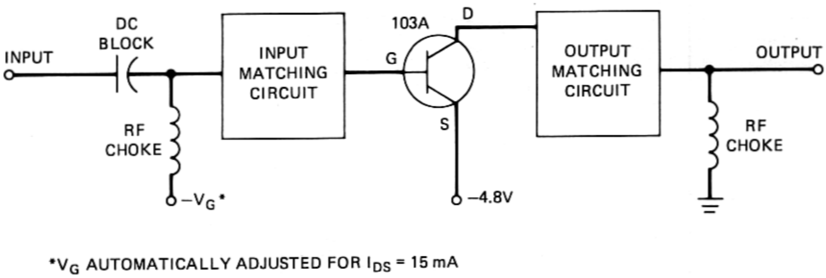

Fig. 10—Amplifier module (schematic).

VII. PHYSICAL DESIGN

The completed amplifier is shown in Figs. 3 and 7. The aluminum housing is die cast in two parts. The stripline center conductor is stamped in a single piece from sheet brass. Interlocking molded plastic locating rings are used to locate both the circulator ferrites and the center conductor in the lower housing channel. The printed circuit board with power regulator and alarm circuits (Fig. 11) is mounted on the bottom side of the lower housing.

VIII. AMPLIFIER PERFORMANCE AND TESTS

8.1 Tests

In order to meet the requirements in Table I, the amplifier was subjected to several tests, most of which used straightforward test procedures. Special test sets were constructed for noise figure and inter-

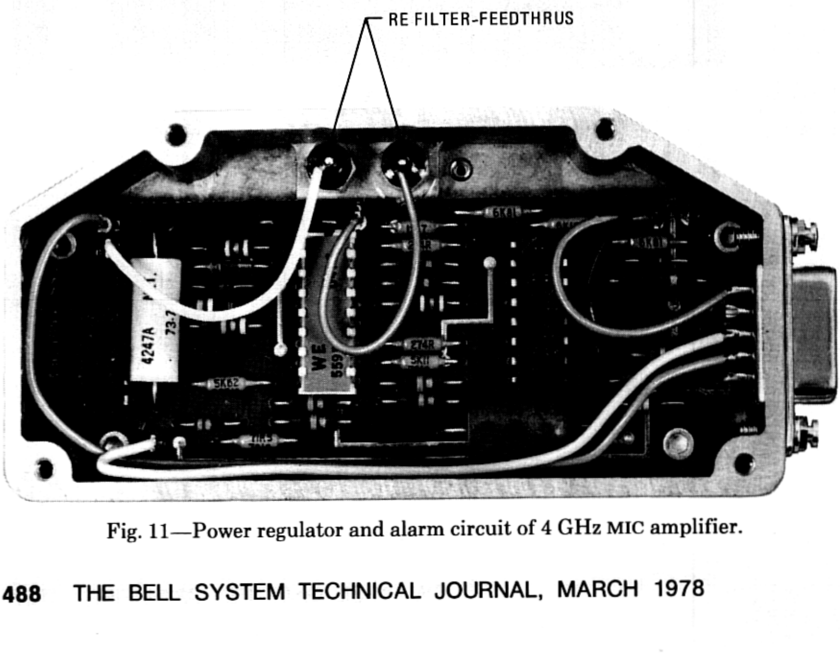

Fig. 11—Power regulator and alarm circuit of 4 GHz MIC amplifier.

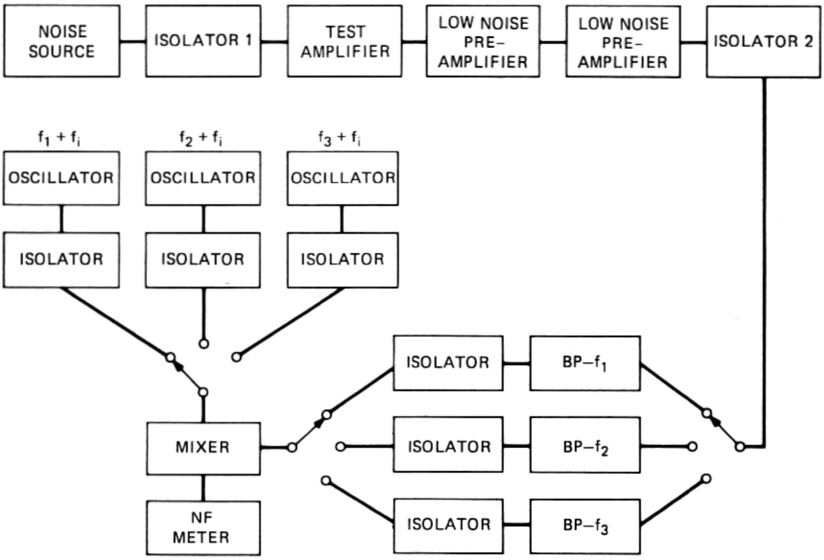

Fig. 12—Complete three-frequency NF test set.

modulation measurements. The noise figure can be accurately and rapidly measured at three frequencies in the test set shown in Fig. 12. Intermodulation (IM) tests were done using a three-tone measurement set. Since not all stations are air-conditioned, a humidity test was started. The amplifier was placed in an 85°C (185°F)—85% humidity environment for two months with DC bias applied. No change in performance was detected. Six field trial models were cycled over the temperature range of 4°C (40°F) to 60°C (140°F) with no significant change in performance.

8.2 Performance

The amplifier is in manufacture at Western Electric Company and meets the requirements summarized in Table I. Typical performance values obtained are:

NF: 1.6–1.8 dB
Input and output return loss: 28 dB
2A-B intercept: 26 dBm
Unpowered transmission loss: 5–8 dB
Gain: 10 dB.

We find that the amplifier tuning arrangement permits the present spread in transistor parameters to be accommodated easily.

IX. CONCLUSION

We have demonstrated a simple 4 GHz microwave amplifier design which achieves a noise figure of 2 dB in manufacture. This has been achieved with a single low noise GaAs field effect transistor in conjunction with a passive failsafe by-pass circuit. It is concluded that the single-ended amplifier with input and output isolator has significant advantages both in performance and in simplicity over the balanced amplifier design for this application. The housing and major piece parts are die replicated so as to fit together with minimal assembly effort. Tuning screws are provided to accommodate variations in transistor characteristics and to allow relaxed piece part tolerances.

X. ACKNOWLEDGMENTS

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