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FINAL REPORT

THE DEVELOPMENT OF AN S-BAND PARAMETRIC AMPLIFIER USING NEW TECHNIQUES FOR GAIN STABILIZATION

SUBMITTED NOVEMBER 1965

ON

CONTRACT NAS8-11817

WITH

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GEORGE C. MARSHALL SPACE

FLIGHT CENTER

M I C R O W A V E   P H Y S I C S   C O R P O R A T I O N

420 Kirby Street
Garland, Texas

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SUMMARY

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This report describes the results of a research and development program investigating parametric amplifier gain stabilization using temperature sensing and compensation techniques. The work included development, testing, and delivery of an operating laboratory model of an S-band amplifier tuned to 2.276 Gc. This amplifier should have a wide variety of applications in communications or tracking systems in which temperature changes are sensed and corrected for, thus eliminating the requirement for a controlled environment.

Author

PROJECT OBJECTIVE

The work undertaken on this contract was directed to develop techniques for gain stabilization of an S-band parametric amplifier by temperature sensing and compensation.

Design goals included eliminating the requirement for a carefully controlled environment and minimizing operational warm-up time and power requirements. High system reliability and elimination of manual adjustments for normal amplifier performance were practical objectives for the deliverable laboratory model. Efforts were expected to result in an amplifier which will have a wide application in a variety of communication or tracking systems requiring minimum maintenance and simplified operation.

The laboratory model S-band parametric amplifier was to meet the following specifications:

a. General:

Center frequency	2276.424 Gc
Bandwidth	As determined by phase response requirements
Noise figure--maximum	2 dB
Gain	17 dB
Gain Variation--design goal	$\pm$ 0.5 dB
--maximum	$\pm$ 1.5 dB
Spurious response rejection --design goal	80 dB
Intermodulation rejection (all orders) --design goal	80 dB
	80 dB

Operating temperature range	-30^{o} C to $+75^{o}$ C
Phase Response	
Differential Phase Shift between 5wo signals 3.2 Gc apart, that may encounter Doppler frequency shifts of 80--maximum	20^{o}
Differential phase variation over 3.2 Gc bandwidth due to all sources--design goal	1^{o}
Phase linearity over 3.2 Gc bandwidth--design goal	1^{o}
Pump power leakage	-20 dB
Warm-up time	2 seconds
Primary power	110/220 V $\pm$ 10%, 60 cps

b. The amplifier shall not limit on noise, but shall be able to withstand an input signal level of -65 dBm without serious degradation in performance

c. The amplifier shall not require manual tuning or adjustment to remain within specified limits.

d. The amplifier shall be packaged in a standard 19-inch rack mounting.

e. Appropriate outputs for monitoring and recording amplifier performance shall be provided, including pump power, etc.

f. The amplifier shall have a certified 98 percent probability of normal operation over a period of two years, including on-off cycling, without degradation of performance outside the specified limits.

TECHNICAL DISCUSSION

GENERAL. Several new techniques were employed in the design of the amplifier. Among these was the elimination of a varactor diode bias source through the use of self-bias and open loop temperature sensing and control. Before discussing these techniques in detail, several other features of the design will be described and their effect on the operation discussed.

A five-port low loss circulator was employed to give greater than 40 dB of isolation on both the input and output ports of the amplifier. This not only improved input and output termination VSWR but gave sufficient isolation of the amplifier from external connections to eliminate causes of gain variation which might be present due to external VSWR.

The amplifier system was constructed with as many solid state components as was feasible to provide the highest reliability. The pump source was powered by a silicon d-c power supply with sufficient load and line regulation to eliminate gain variations due to external power fluctuations.

The amplifier was designed to be controlled with a minimum number of mechanical or electrical adjustments and is free of tuning once the desired frequency and gain are set. Pump frequency adjustments are eliminated by the use of a fixed-frequency solid state source. Signal frequency is adjusted by varactor diode bias adjustments and the gain is controlled by the amount of pump power supplied to the varactor mount. The varactor mount was designed to provide the simplified controls using conventional techniques and will not be discussed here, but it should be pointed out that it was necessary to achieve the simplified control operation before investigating gain stabilization techniques. Essentially, it was necessary to have simplified control so that once variations are sensed there would be an easy way to realign the amplifier and achieve gain stabilization.

A functional block diagram, figure 1, identifies the major components of the amplifier system.

DESIGN CONSIDERATIONS. Nondegenerate varactor diode parametric amplifiers are negative resistance amplifiers which require a constant difference between external and internal resistance to maintain stable gain. Variation in ambient temperature will cause the internal negative resistance to change. This change in internal resistance can be related to changes in individual parameters which make it up from an examination of the amplifier gain expression. It is the purpose of this discussion to show the effect on gain of changes in pump power level and varactor diode series resistance. These two factors are normally greatly affected by change in temperature.

AMPLIFIER EQUIVALENT CIRCUIT AND GAIN FORMULA. The amplifier equivalent circuit and gain formula used here are taken from Blackwell and Kotzebue[1]. The equivalent circuit for the amplifier with a ferrite circulator is shown in figure 2. The power gain for the amplifier is:

$$G = 4 R_g^2 / (R_{T1} - R)^2 \qquad (1)$$

where:

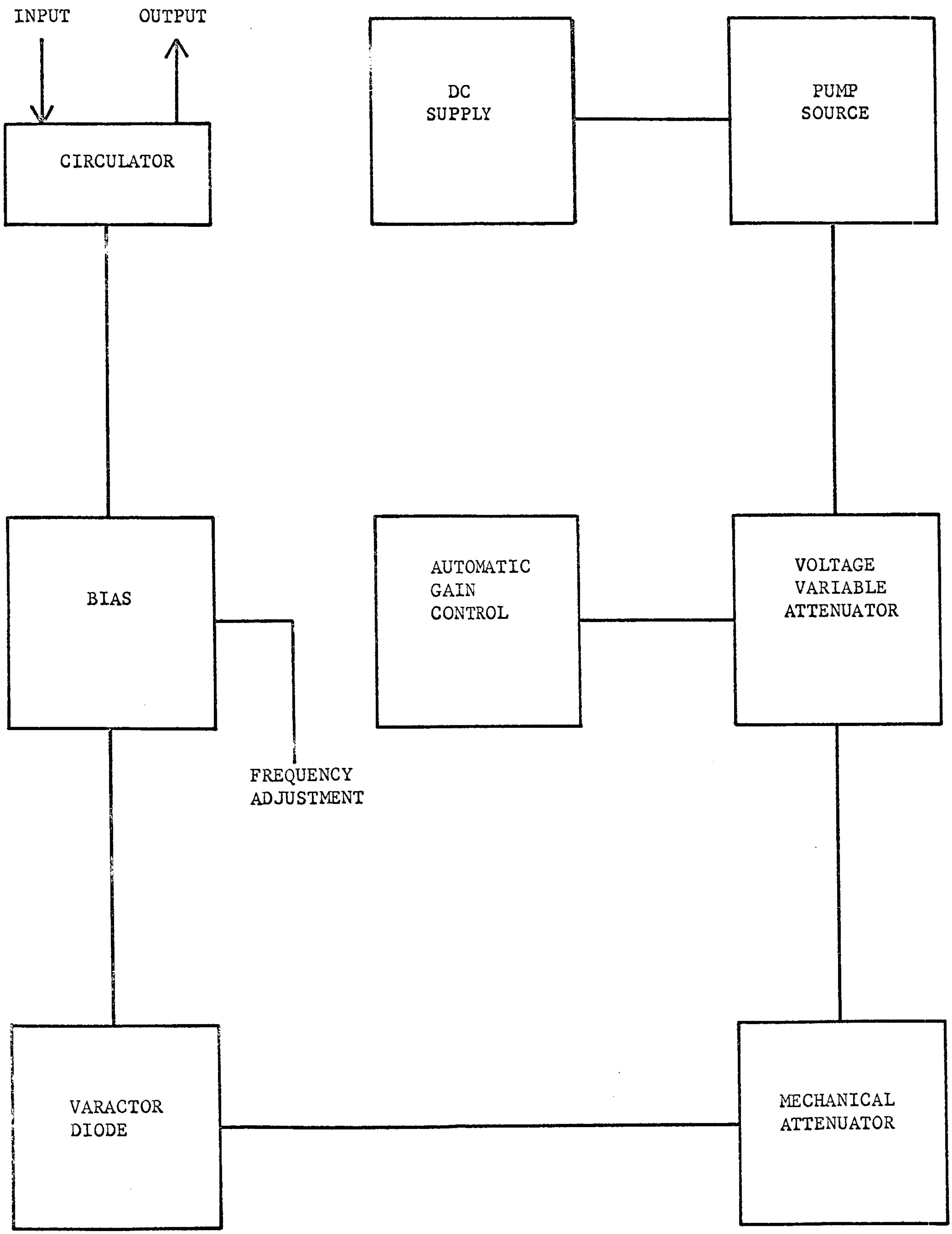


FIGURE 1. SYSTEM BLOCK DIAGRAM

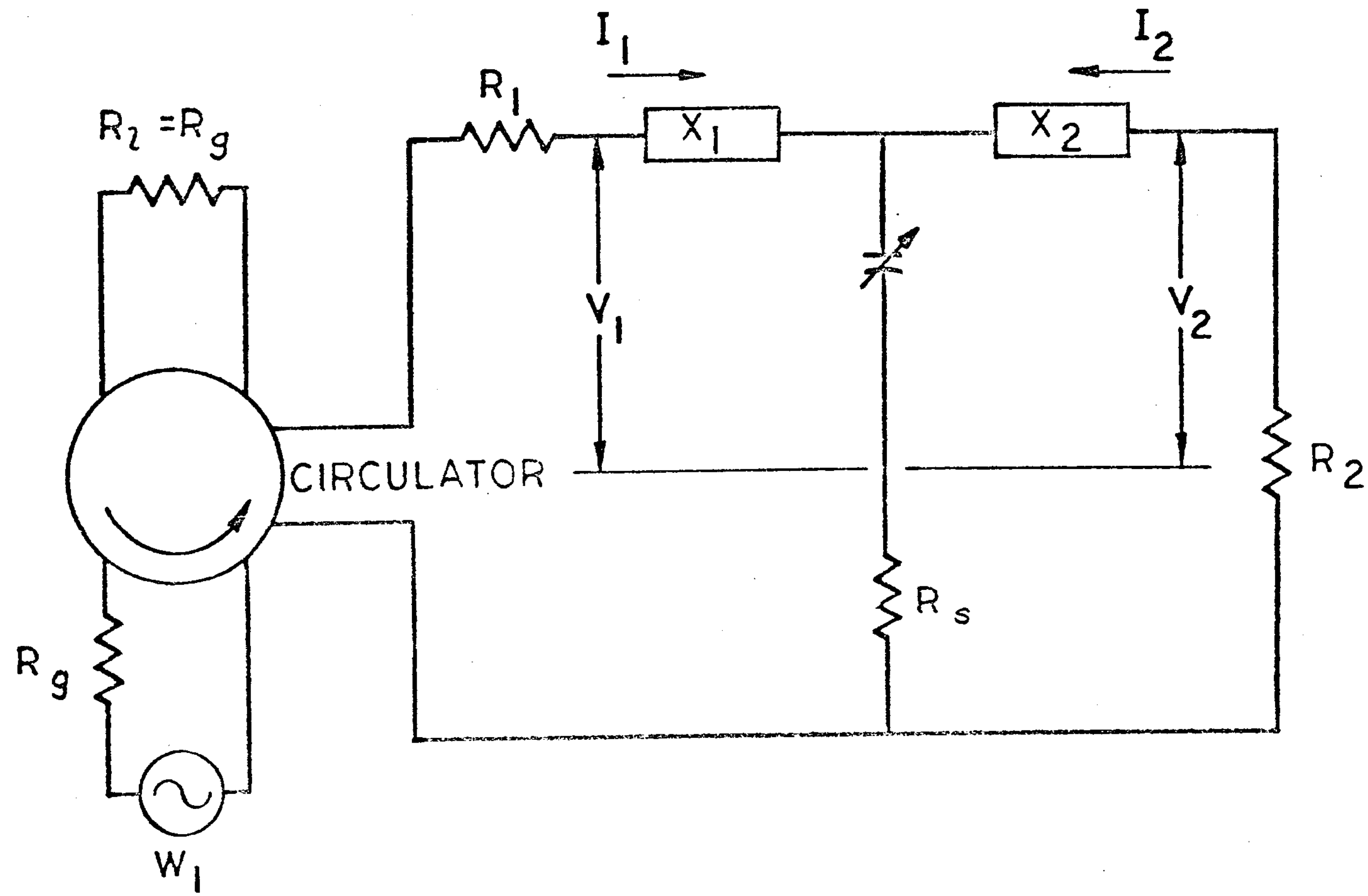


Figure 2. Circuit Model for the Negative Resistance Parametric Amplifier Operated with Circulator

R_g = generator resistance =

Z_o of input line connecting to varactor diode

R_{T1} = $R_g + R_s$; R_s = series resistance of the varactor diode

$$-R = \frac{-\gamma^2}{\omega_1 \omega_2 C^2 R_s}$$

γ = $\Delta C/2C_o$, the normalized capacitance variation resulting from applying pump voltage

C_o = junction capacitance of the varactor diode at operating point

ω_1 = signal angular frequency

ω_2 = idler angular frequency

In order to examine the effect of normally variable factors on gain, Equation (1) may be written as follows:

$$G = \frac{4\,R_g^{\,2}}{\left[R_g + R_s - \frac{\gamma^2}{\omega_1 \omega_2 C^2 R_s}\right]^2} \tag{2}$$

By using a circulator at the amplifier input to isolate the effect of variable external impedances such as might be caused by a rotating antenna, R_g becomes the characteristic impedance of the coaxial line connecting to the diode. This impedance, and thus R_g, will vary only slightly, if at all, over a very wide range of temperature and can be considered to be constant in the practical case. The frequencies represented by ω_1 and ω_2 are practically constant also, especially if the pump source is controlled in frequency as would be the case for a solid state source. The diode capacitance, C, is temperature sensitive; however, the effect is

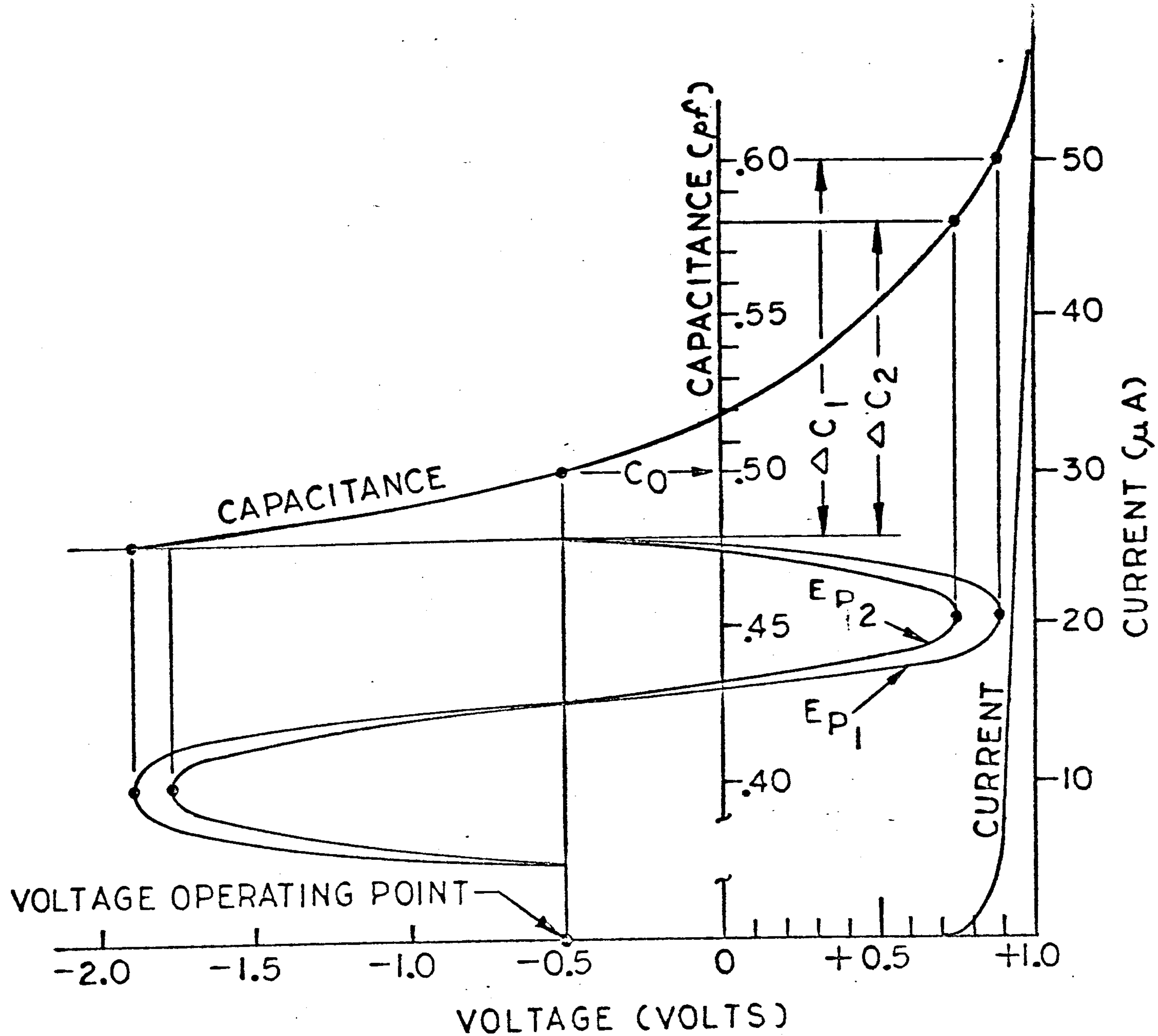


Figure 3. Capacitance and Current Versus Voltage for Varactor Diode in Parametric Amplifier Application

a slight detuning of the amplifier center frequency which is not troublesome for an amplifier design of sufficient bandwidth. The remaining factors are γ and R_s, each of which is sensitive to changes in temperature. The factor γ is affected by temperature indirectly as a result of pump power level being variable with temperature.

At this point, a design example should be examined in order to determine the magnitude of the effects of variation in γ and R_s. It can be shown theoretically and from practical design examples that a noise figure less than 2.0 dB can be obtained at 2300 Gc with commercially available varactor diodes pumped at 13,500 Gc. Sufficient bandwidth can also be obtained; therefore, the following discussion will apply to obtaining the required gain in the amplifier.

CHARACTERISTIC PARAMETERS FOR VARACTOR DIODE PARAMETRIC AMPLIFIER

$f_s = f_. = 2,300$ Gc

$f_p = 13,500$ Gc

$f_i = f_2 = 11,200$ Gc

C at -0.5 volts = 0.5 Pf

$R_s = 2.50$ ohms at 25° C

$\gamma = \Delta C/2C_o = 0.13$

$R_g = 30$ ohms

Substitution of the above values into equation 2 results in a calculated gain of 17.35 dB. The operating average capacitance and bias voltage point for this amplifier are shown in figure 3. The curves of figure 3 show capacitance versus voltage and current versus voltage for a typical gallium arsenide varactor diode. The relationship of γ ($\gamma = \Delta C/2C_o$) to the magnitude of the pump voltage may be seen graphically from this curve. For the amplifier example worked out above, the pump voltage required to obtain $\gamma = 0.13$ is 2.9 volts peak-to-peak with the operating voltage point set at -0.5 volt with a separate biasing source such as a battery. A reduction in pump voltage of 10 percent would change γ from 0.13 to $\gamma = 0.12$. The gain would change from a value of 17.35 dB to 14.75 dB. Similarly, the effect of an increase in pump voltage can be determined. At least 10 percent change in pump voltage, about 0.4 dB, can be expected from most uncompensated pump sources available over the temperature range from -30 to +60° C.

GAIN COMPENSATION BY AUTOMATIC ADJUSTMENT OF VOLTAGE OPERATING POINT. The preceding discussion has shown that a decrease in γ caused by a decrease in pump voltage will produce a correspondingly large decrease in amplifier gain. This occurs because the operating point is fixed at -0.5 volts. If the operating point were shifted to a lower negative voltage, γ would remain very close to its value prior to pump voltage decrease because of the high degree of nonlinearity in the capacitance curve in the range from 0.7 to 1.0 volts. From figure 3, it may be seen that a shift in the operating point to -0.36 volt from the original -0.5 volt point would almost exactly compensate for the drop in peak pump voltage from 1.40 volts to 1.26 volts. At the new operating point, C_o would be 0.505 rather than 0.500 pf. This change in capacitance would cause a calculated change of 9 Mc in amplifier center frequency; however, the amplifier can be designed with sufficient bandwidth to maintain gain at the design center frequency.

The method of biasing the amplifier to achieve an automatic shift in the operating point is shown schematically in figure 4. With pump voltage applied to the varactor diode, current flowing in the varactor diode and biasing resistor will build up a negative voltage at the diode anode. This action will bias the diode negative from the zero voltage point existing prior to application of pump voltage. The point reached depends upon the magnitude of the pump voltage, the amount of biasing resistance, and the E-I characteristic of the varactor diode. For the amplifier example discussed, a bias resistance of about 0.5 megohms and an average diode current of 1 μA would establish the -0.5 volt operating point. A decrease in pump voltage causes a decrease in diode current and bias voltage, thus shifting the operating point to a less negative value. As previously discussed, this action results in retaining very closely the same value for γ as existed prior to the pump voltage change.

The diode self-biasing method of gain stabilization providing automatic adjustment of voltage operating point was used successfully. While not exactly compensating for pump voltage changes, the method showed a five-to-ten times improvement in gain stability for pump power variations.

For gallium arsenide varactor diodes the effective series resistance has been observed to decrease about 10 percent for a temperature change from 25° C to -30° C and to increase about 3 percent in going from 25° C to 60° C. For the amplifier example with 17 dB gain at 25° C, the gain should vary from 16 dB at 60° C to 21 dB at -30° C. Observations on the laboratory model showed such a gain variation and also that selecting the proper pump power would achieve 17 dB of gain over the entire temperature range.

TEMPERATURE COMPENSATION. To compensate for changes in diode resistance

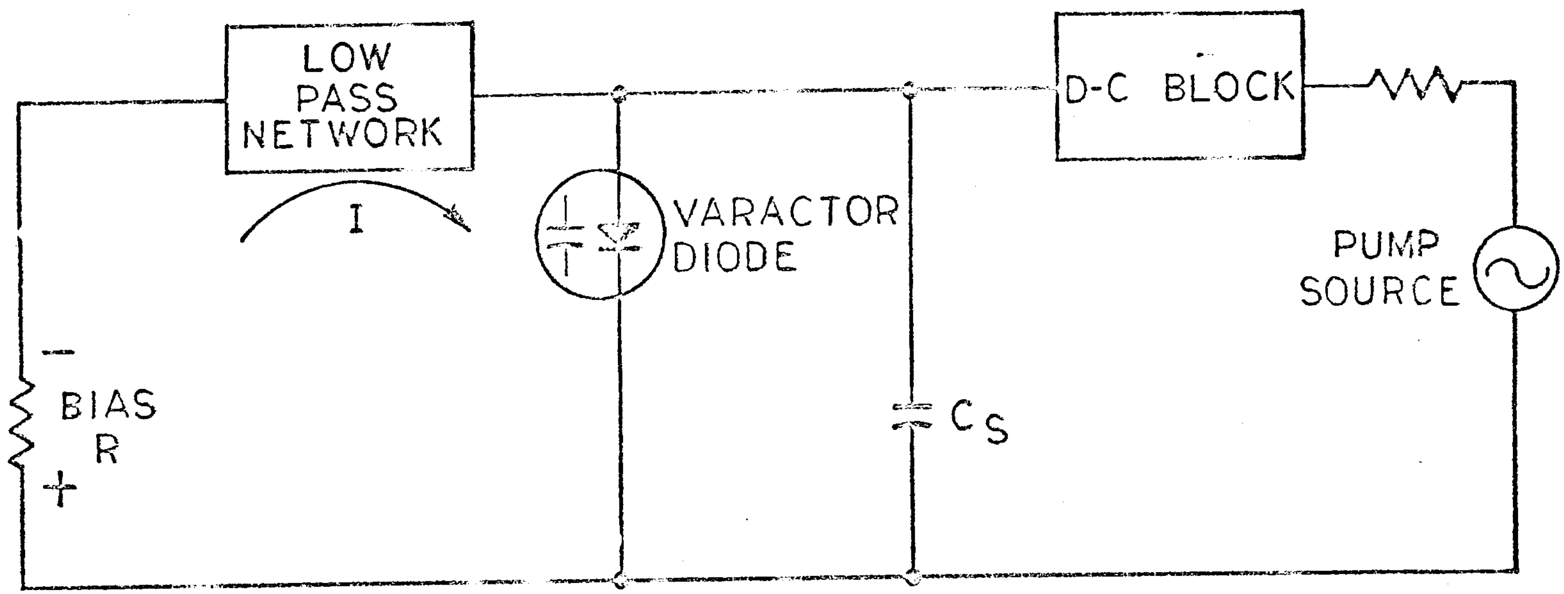
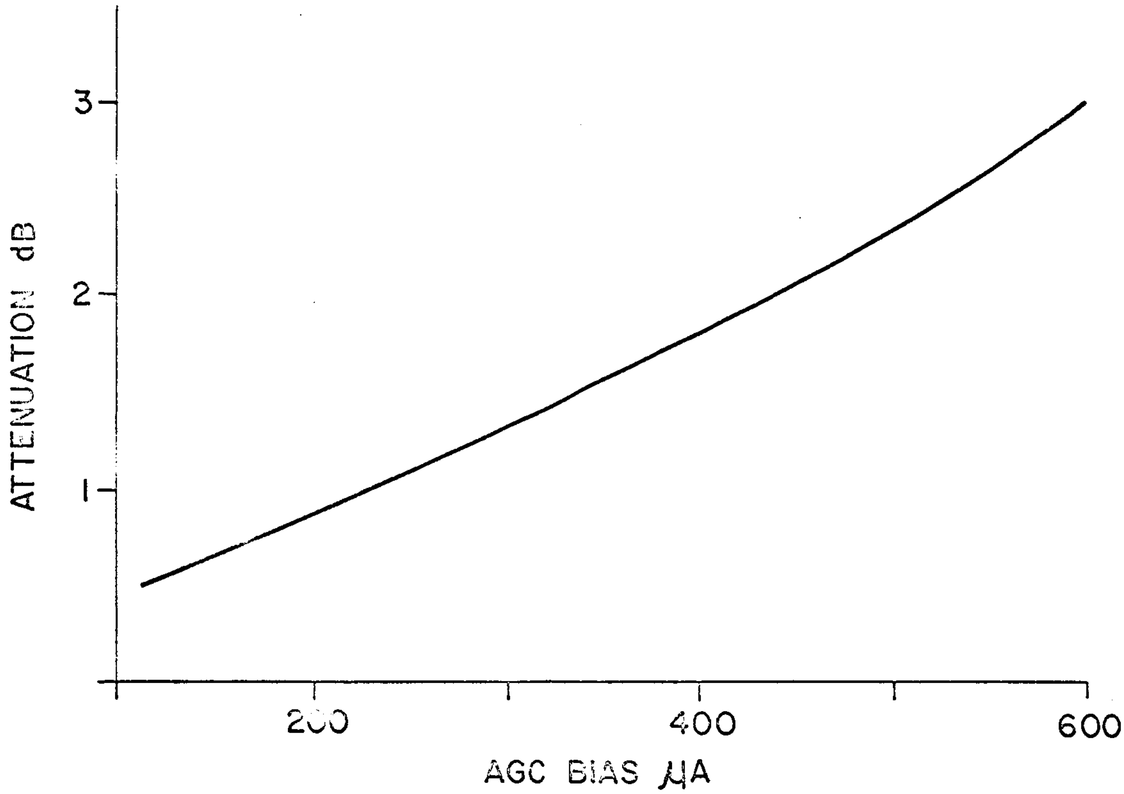
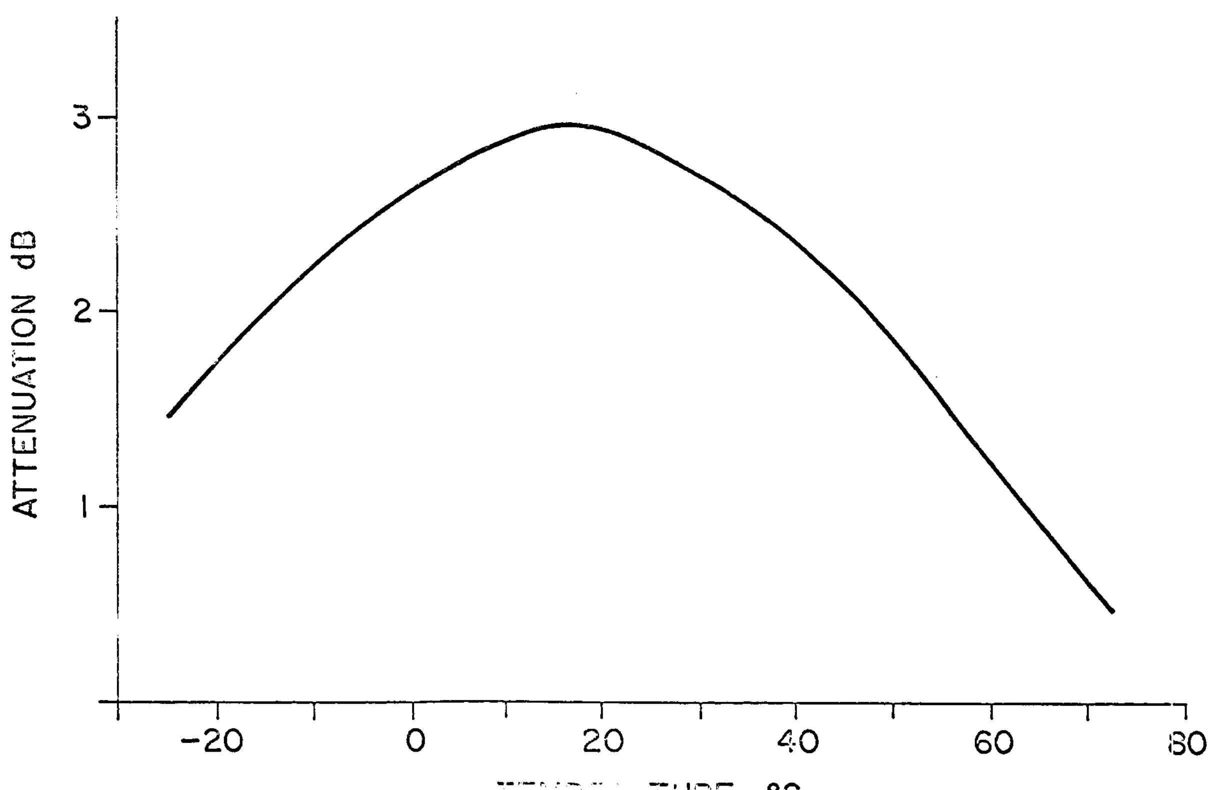


Figure 4. Simplified Schematic of Varactor Self-Biasing Arrangement

and pump power variations not corrected by the self-bias arrangement, an open loop temperature sensing and controlling circuit was employed. The circuit used a voltage-variable attenuator in the pump line to vary the power. A temperature-sensing device using thermistors and diodes was used to supply a varying drive voltage to the attenuator. This method was used to eliminate the need for a controlled system temperature such as would be provided by heaters and elaborate box insulation to prevent diode and pump changes. Further, an open loop system was chosen to eliminate the need for the pump power detection-and-feedback arrangement that has been used in other systems. In a closed system the sampling device would need to be temperature-compensated itself. To provide simplicity in control circuits, the open method was used. First, data was taken on the amount of attenuation needed in the pump line to maintain the amplifier at 17 dB of gain over the temperature range. Figure 6 shows the results. The voltage-variable attenuator utilized a PIN semiconductor diode mounted in a waveguide structure to provide a variable loss with bias voltage. Figure 5 shows typical attenuation versus bias. The final step in the design of the control circuit was to build a bias supply that would drive the attenuation in the prescribed manner shown in figure 7. Several circuits were tried using various combinations of components. A differential amplifier arrangement proved too complicated and unreliable. The final circuit shown in figure 8 utilized two diodes and a voltage divider network to provide the needed output. Figure 7 shows the bias requirements diminishing at the high and low temperature extremes with a maximum value at room temperature. The solid state source affected the curve at high temperature by a decrease in pump power while the R_s of the diode


ATTENUATION dB
3
2
1
200
400
600
AGC BIAS μA
FIG 5.


ATTENUATION dB
3
2
1
-20
0
20
40
60
80
TEMPERATURE °C
FIG 6.

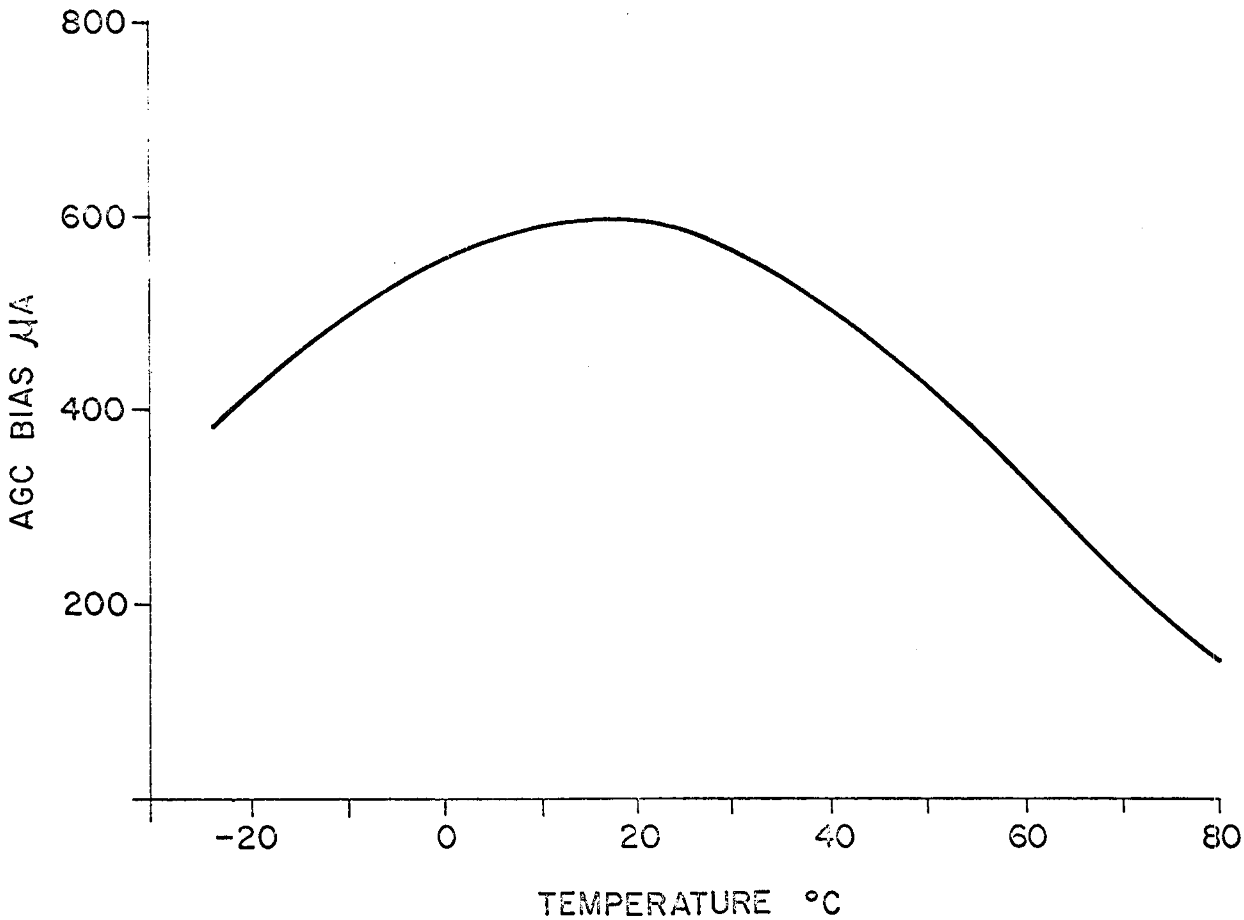
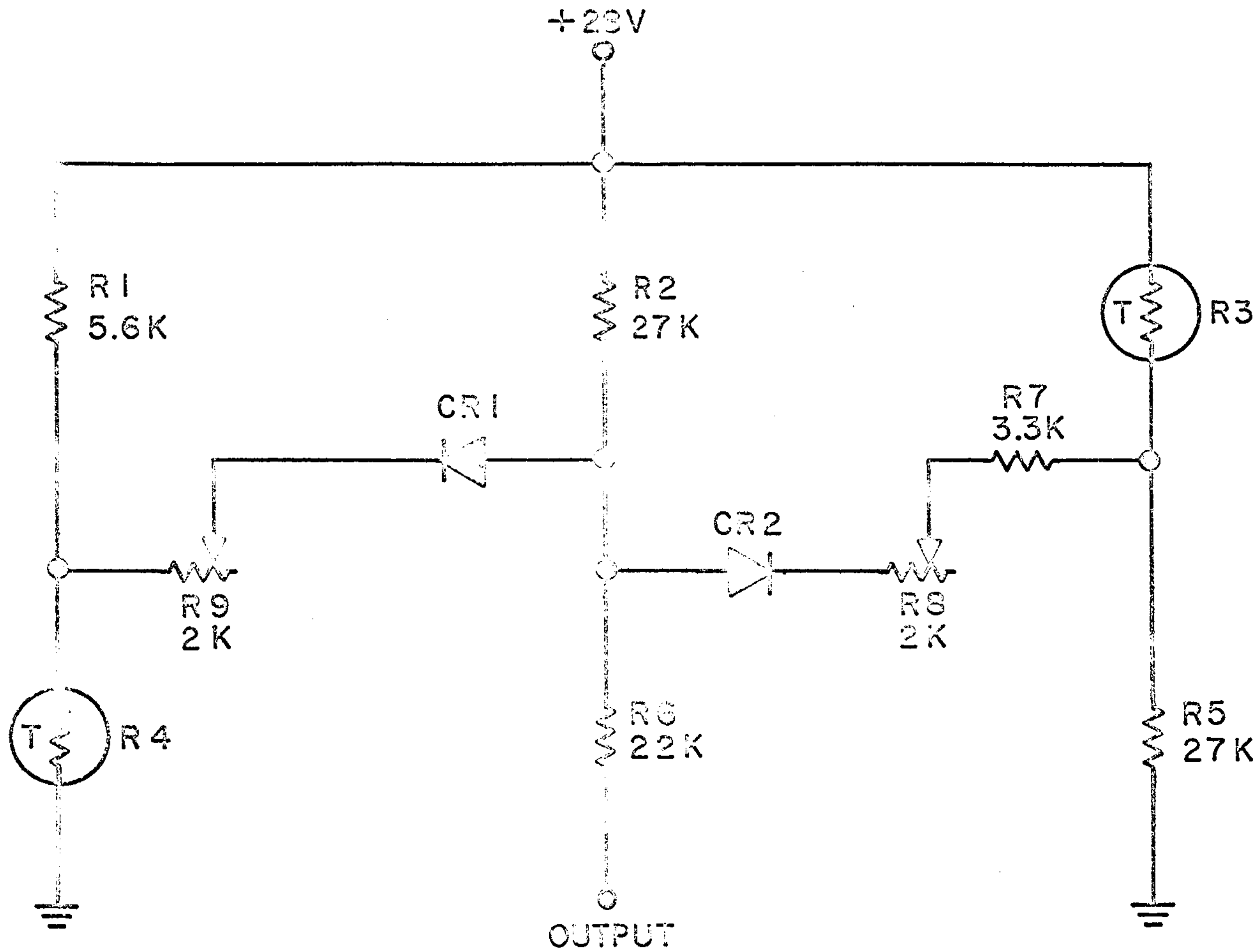


FIG 7.



ALL RESISTORS ARE 1/2 WATT ± 10%
R8 AND R9 ARE BOURNS TRIMPOTS
CR1 AND CR2 ARE MOTOROLA 1N4002
R3 AND R4 ARE VECO THERMISTOR – 36S1, 6300 OHMS

Figure 8. AGC Assembly Schematic Diagram

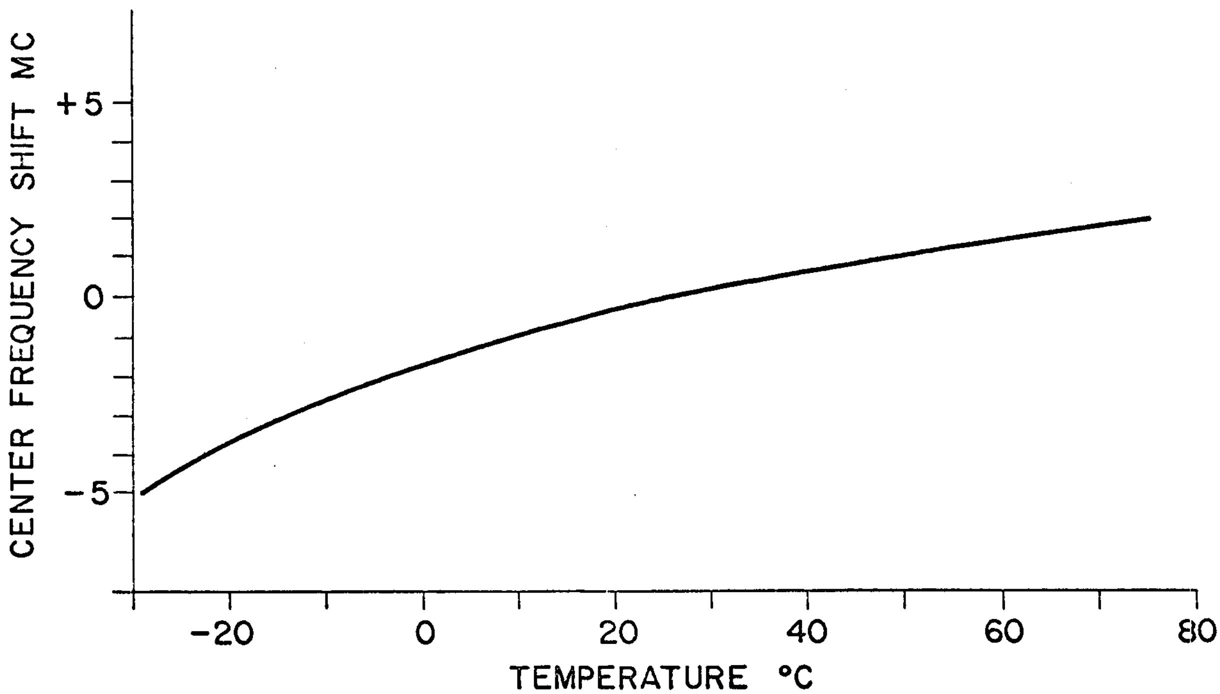
effected the gain at low temperatures. The overall gain with AGC compensation varied $\pm$ 1.5 dB between -25° C and +55° C and slightly worse on the ends. This is shown in figure 10. The center frequency shift is shown in figure 9.

LABORATORY MODEL. The unit is a gain-stabilized, non-degenerate parametric amplifier, designed for low noise amplification at 2.28 Gc. Automatic gain stabilization in an uncontrolled environment is achieved by means of a temperature sensing and compensation system. Any temperature change that would ordinarily cause gain variation is sensed and a compensating voltage is applied to the PIN diode in a voltage-variable attenuator to control the output of the solid-state pump source. The varactor diode is self-biased to improve stability and eliminate the need for a bias supply. Turn-on is essentially instantaneous and after the gain and center frequency have been set, the parametric amplifier may be operated unattended. The parametric amplifier and associated waveguide assemblies, attenuators, circulators, directional coupler, modular power supply, modular pump source, AGC assembly, blower, and control panel are all contained in a single unit, packaged for rack mounting. It should be noted that this operational configuration could be packaged as a much smaller unit. A system schematic is shown in figure 11. Figure 12 shows the entire unit and its components.

The unit exhibited the following electrical characteristics:

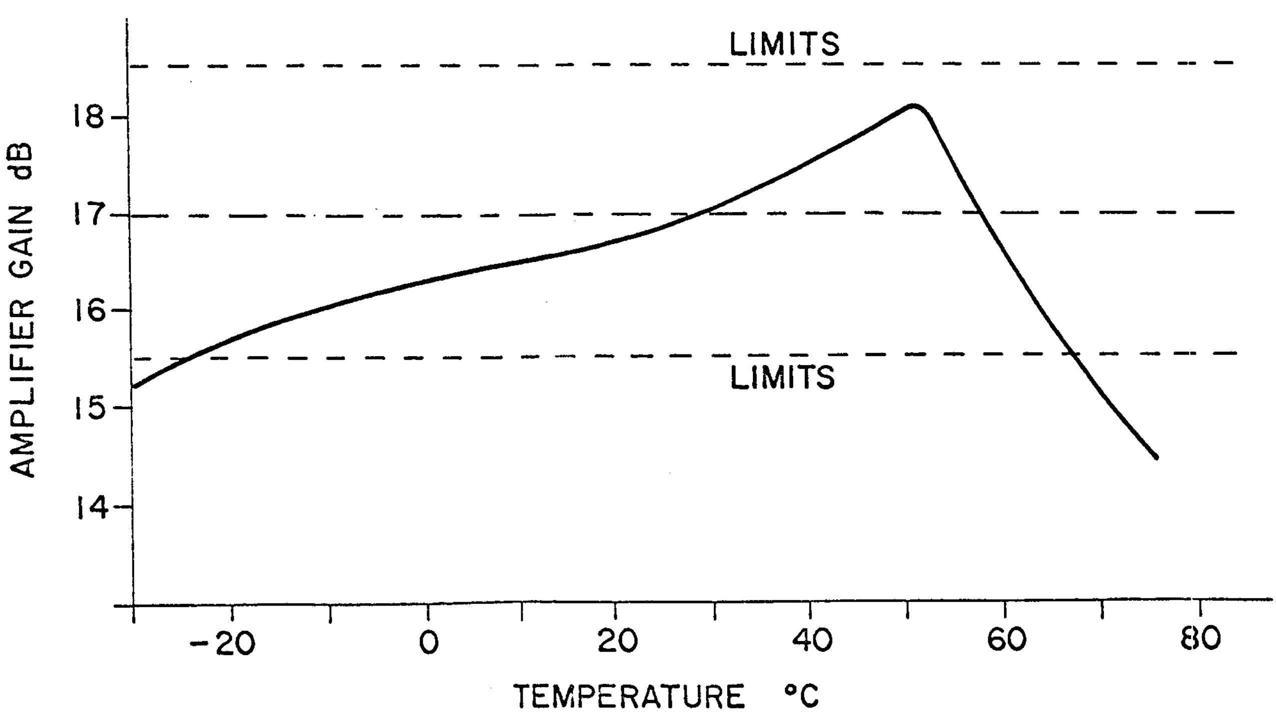
ELECTRICAL CHARACTERISTICS

Power Input	110 vac, $\pm$ 10%, 60 cps
Center Frequency	2.28 Gc, $\pm$ 10 Mc
Bandwidth	25 Mc, minimum (3 dB)
Noise Figure	2 dB, maximum
Gain	17 $\pm$ 1.5 dB



CENTER FREQUENCY SHIFT MC
+5
0
-5
-20
0
20
40
60
80
TEMPERATURE °C

FIG 9.



LIMITS
LIMITS
AMPLIFIER GAIN dB
18
17
16
15
14
-20
0
20
40
60
80
TEMPERATURE °C

FIG 10.

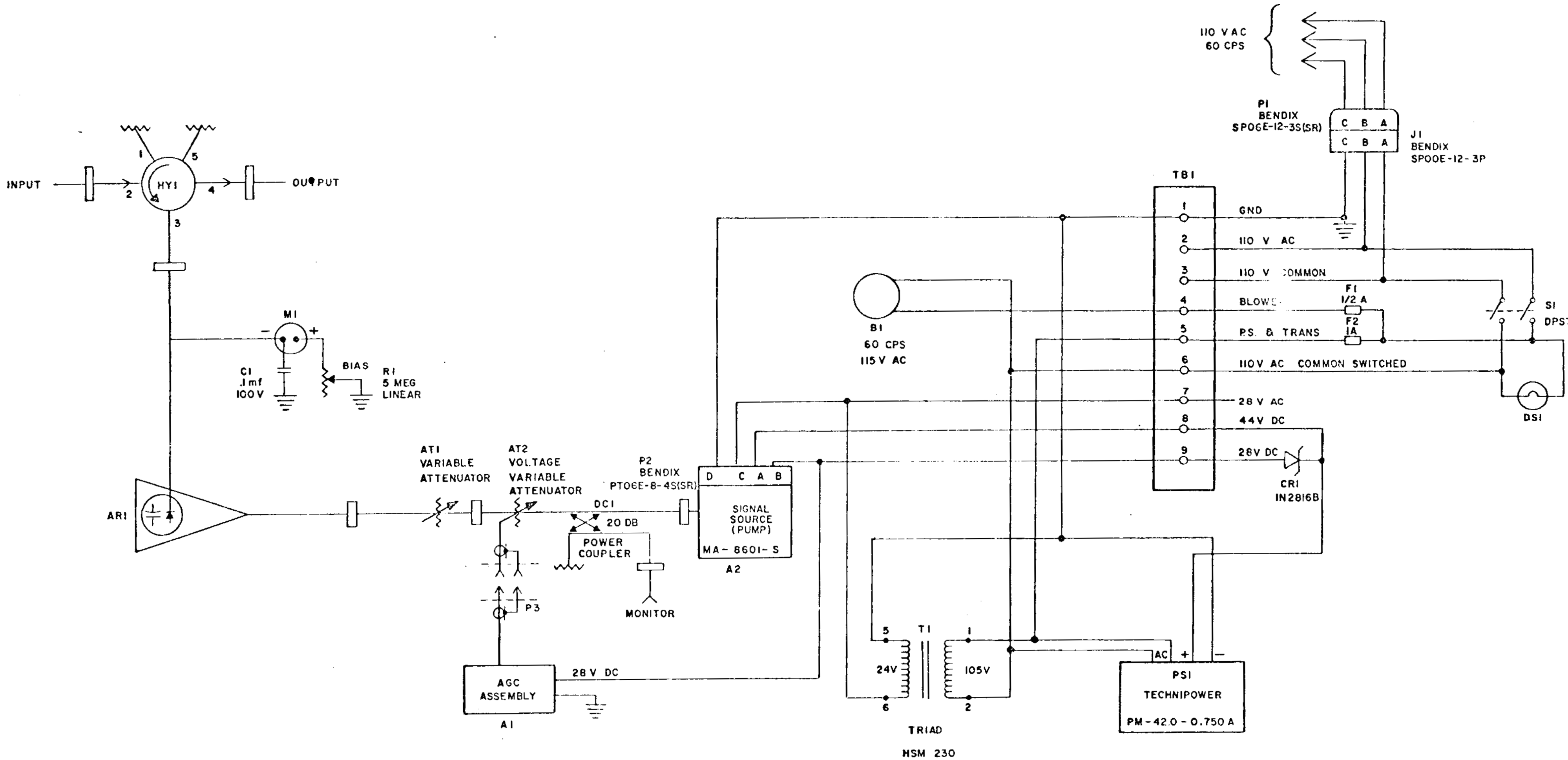
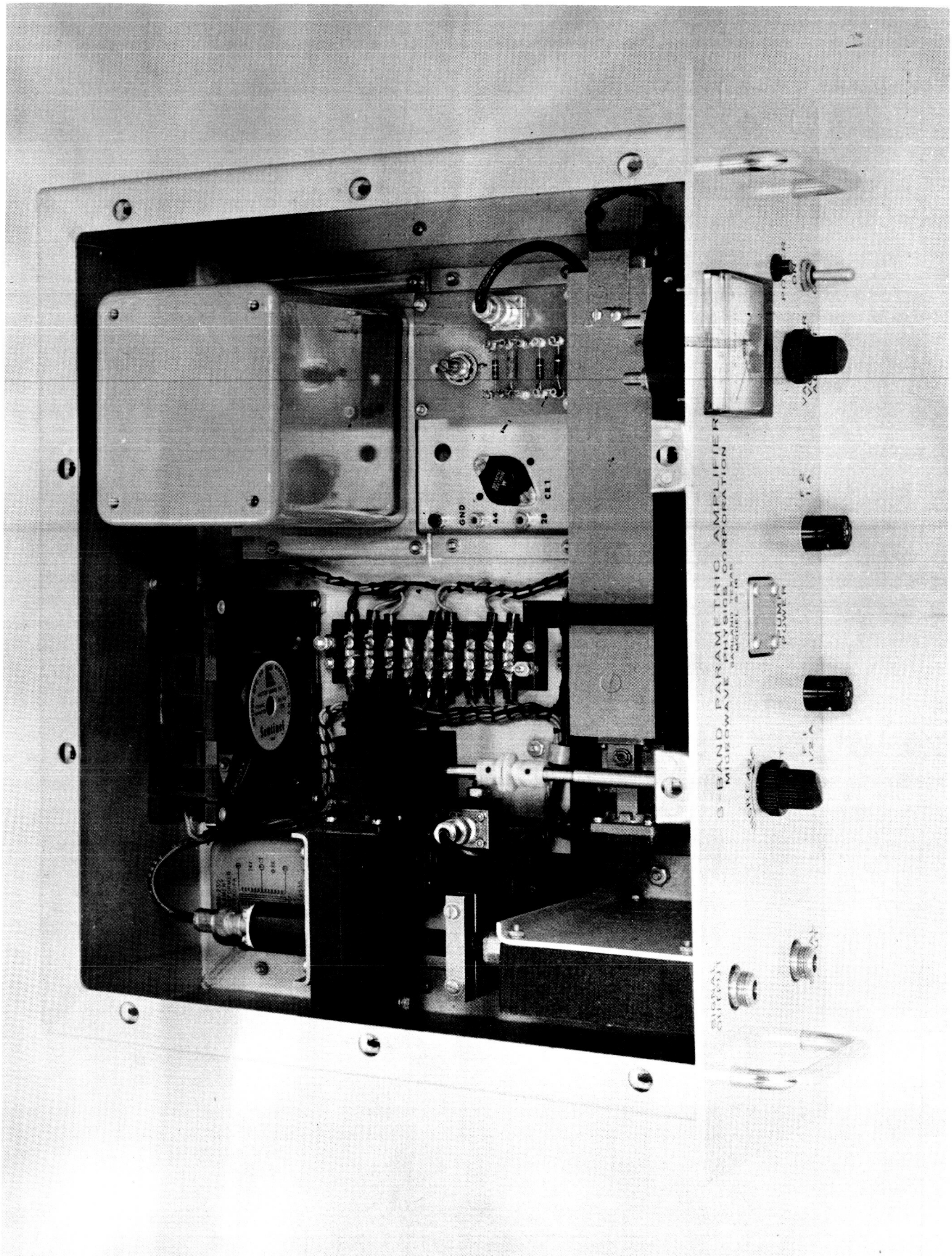


Figure 11. S-Band Parametric Amplifier, Model S-16, Schematic Diagram


S-BAND PARAMETRIC AMPLIFIER
MICROWAVE PHYSICS CORPORATION
GARLAND TEXAS
PUMP POWER
SIGNAL OUTPUT
GND
44
28
CR1

ELECTRICAL CHARACTERISTICS (Cont)

Differential Phase Shift Between Two Signals 3.2 Gc Apart	20° Nominal
Pump Frequency	13.5 Gc
Warm-up Time	2 Seconds
Operating Temperature	-30°C (-21° F) to 75° C (167° F)
Dimensions	19 x 7 x 14½ inches
Weight	40 Pounds

Optimum phase stability performance was achieved by designing the unit with adequate bandwidth and attaining the described gain stability. A complete set of operational data was reported in "Acceptance Test Procedure for Parametric Amplifier System for NASA Contract NAS 8-11817" submitted June 1965 - MPC No. 12310.

RELIABILITY. One of the objectives of this development was to obtain a high system reliability. To achieve this reliability, the design of the system was directed to eliminate low-MTBF devices such as klystrons and vacuum tubes, and to employ circuits with as few components as possible. Solid state devices were used wherever feasible and electrical stress on the components was kept as low as was practical.

As a result of this design, a system MTBF of greater than 7,000 hours was obtained. This figure is a conservative estimate of system life. A list of the major components and their MTBF is given below. Some MTBF were estimated as data was not available.

UNIT	MTBF (Hours)
Paramp Assembly	75,000
Power Supply	25,000
Pump Source	25,000
AGC Assembly	35,000
Passive Components and Switches	50,000

RESULTS OF THE STUDY. Several important conclusions can be drawn from the study. First, it is possible to design a highly reliable, compact, automatically controlled parametric amplifier. Second, the amplifier can operate at a high level of performance over wide temperature ranges without the need for a controlled environment. Third, simplified compensation networks can be used to obtain gain stability.

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2. NAVWEPS 60-65-502 - Handbook Reliability Engineering

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