A VHF Hybrid Parametric Amplifier

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***Abstract*—This paper describes the design and performance of a VHF hybrid parametric amplifier at 30 MHz. A noise temperature of 18 K coupled with a 6-dB gain and 6-MHz bandwidth is obtained.**

I. INTRODUCTION

A COMPANION PAPER [1] calculates the theoretical gain, bandwidth, and noise performance of the hybrid parametric amplifier.

This paper details the design of a VHF hybrid parametric amplifier with a UHF pump and compares the observed performance with that predicted theoretically.

The VHF band was selected because of one of the attractive features of the hybrid parametric amplifier—the noise figure is lower than that of a resonant parametric amplifier at the same frequency.

II. AMPLIFIER DESIGN

The hybrid parametric amplifier consists of a nonresonant signal circuit forming part of an artificial transmission line and a resonant idler. A complete amplifier system consists of a number of such stages in cascade. The basic circuit is shown in Fig. 1 [1].

The amplifier to be investigated consists of a single T section of transmission line with a varactor in the shunt arm. Ideally no signal current should flow in the idling or pump circuits and similarly no idler current should flow in the pump or signal circuits. As the signal and idler frequencies do not extend into the microwave range it is convenient to use three-dimensional lumped circuit elements for both signal and idling circuits. Idler current is constrained to the idler circuit by means of additional shunt resonant elements put in the series arms of the T section as shown in Fig. 1.

The pump input to the system consists of a series variable capacitor C_p and an external two-stub tuner (not shown).

The dc bias facility consists of a series blocking capacitor C_b and inductance L_b with series resistor R_b.

The circuit is designed to operate at a signal frequency of 30 MHz with an idling frequency of about 800 MHz giving a pump frequency of about 830 MHz.

The varactor of capacitance C_0 and resistance R_d is resonated at the idling frequency by means of the inductance L_I and variable air-spaced capacitor C_I.

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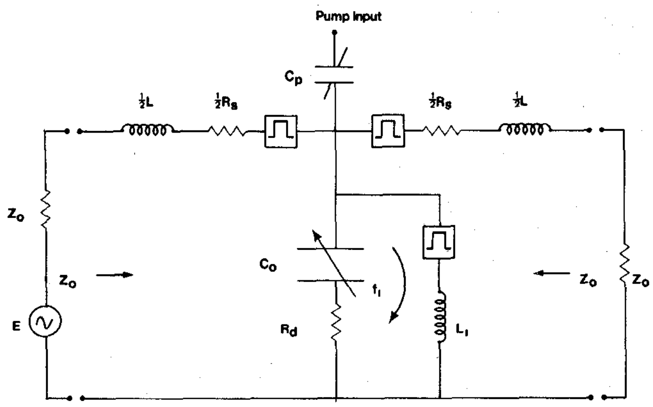

Fig. 1. Single T section of hybrid parametric amplifier.

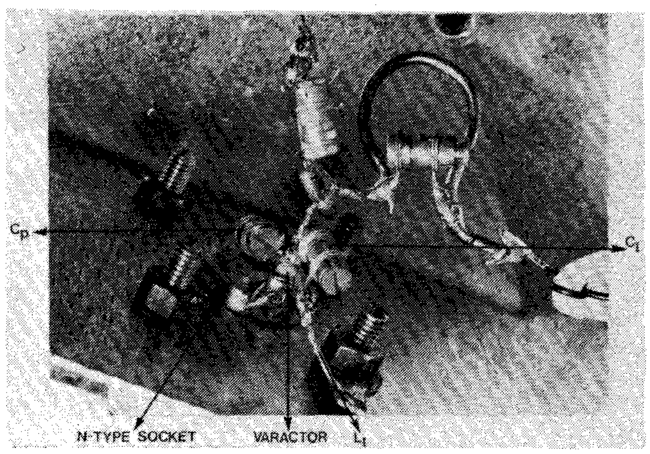

Fig. 2. Photograph of hybrid parametric amplifier.

The T section is fed from and terminated in its characteristic impedance Z_0.

A photograph of the amplifier is given in Fig. 2; the various components mentioned are visible.

A. Selection of Component Values

The available gain of the amplifier G_{av} is given by

$$G_{av} = g + \frac{1}{1-g} \tag{1}$$

where g is given by

$$g = \tfrac{1}{4}\omega_s^2 L C_0. \tag{2}$$

Fig. 3 shows the theoretical variation of G_{av} with g; a gain of 6 dB is predicted with a g value of about 0.7.

Equation (2) enables L to be calculated once the varactor capacitance C_0 is selected. The characteristic imped-

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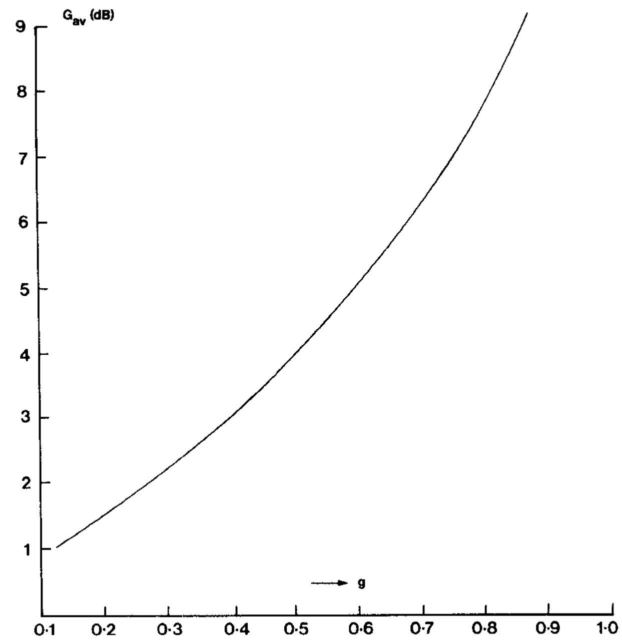


Fig. 3. Variation of gain with g.

ance Z_0 is given by

$$Z_0=\sqrt{\frac{L}{C_0}(1-g)}\ . \tag{3}$$

This can be expressed as

$$Z_0=2\sqrt{\frac{g}{\omega_s^2C_0^2}(1-g)}\ . \tag{4}$$

C_0 is chosen to give a convenient value of Z_0. This leaves the idler frequency ω_I to be determined. This is given by

$$\omega_I=\frac{\gamma^2}{C_0^2\omega_sR_d\left(\frac{Z_0}{2}+\frac{R_s}{4}+R_d\right)}. \tag{5}$$

A varactor with an appropriate value of γ and R_d is selected so that the idler frequency is practically convenient. The dependence of ω_I on G_{av} (through g in (4)) is shown graphically in Fig. 4, with C_0 as a parameter, R_d and γ are assumed constant. This graph shows that a varactor of 15-pF capacitance would require an idler frequency of 850 MHz at 6-dB gain.

We therefore choose a value of 15 pF and calculate L from (2). Variation of gain with inductance is shown in Fig. 5 showing that 5 μH will give 6-dB gain.

Fig. 6 shows the variation of Z_0 with G_{av} and varactor capacitance as a parameter. At 6-dB gain and 15-pF capacitance the characteristic impedance is approximately 320 Ω.

The diode selected for the amplifier is the A.E.I. DC4312B/1 which has a zero bias capacitance of 28 pF and is encapsulated in the S4 package.

Measurement of the varactor shows a capacitance of 11.5 pF at a bias of −4 V. The 4-pF capacitance in the

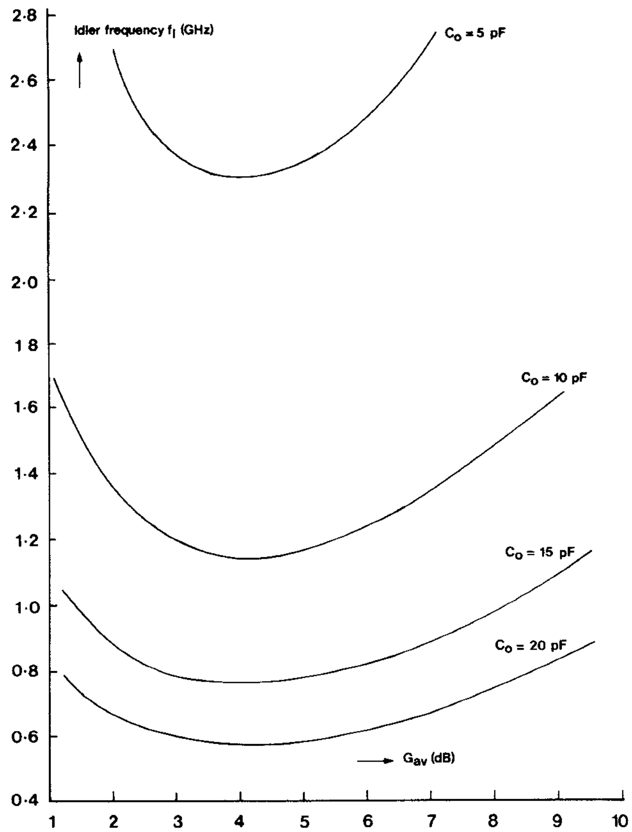


Fig. 4. Computed f_I versus G_{av} for different capacitance C_0 assuming R_d=0.7 Ω and γ=0.16.

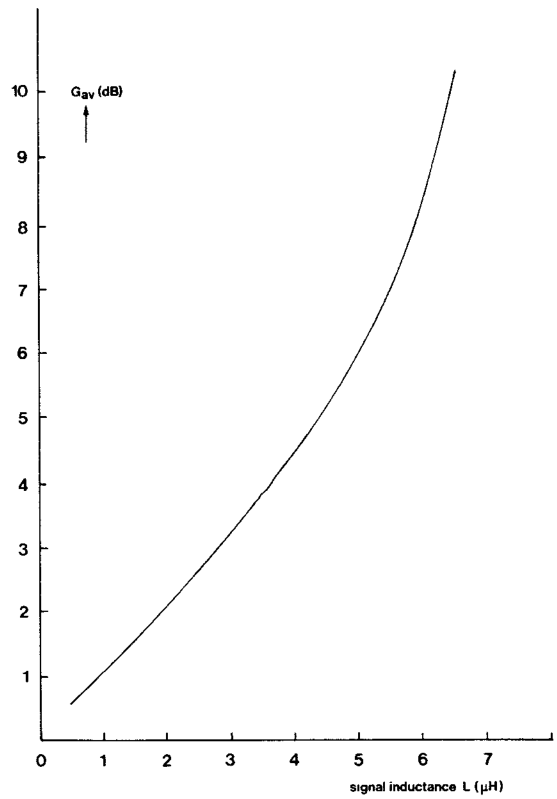


Fig. 5. Showing computed gain (dB) versus signal inductance L (μH) for C_0=15.5 pF and f_s=30 MHz.

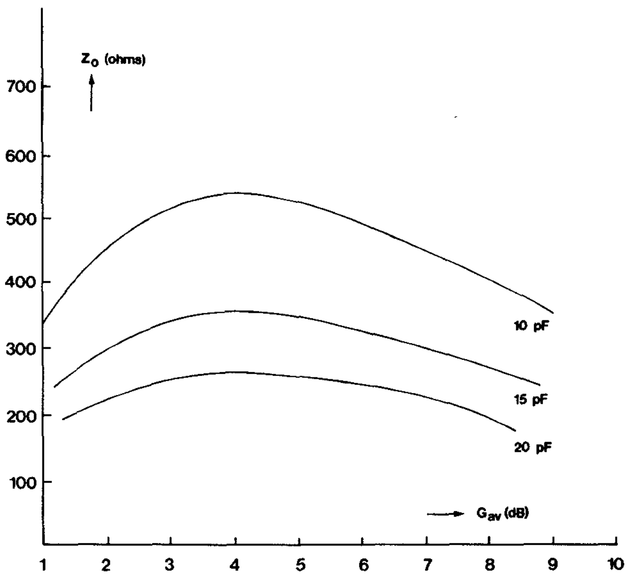


Fig. 6. Computed Z_0 versus G_{av} for different capacitance C.

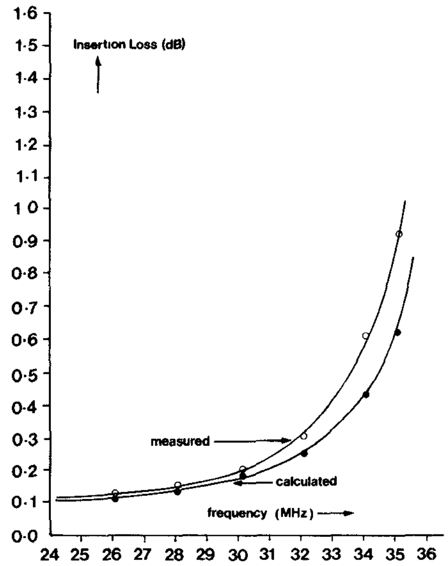


Fig. 7. Graph of measured and calculated insertion loss as a function of frequency.

TABLE I

Signal frequency	30 MHz
Gain	5.9 dB
3-dB bandwidth	8 MHz
Varactor capacitance	11.5 pF
Varactor loss	0.7 Ω
Idler circuit trimmer capacitance	4 pF
Total shunt capacitance	15.5 pF
Signal inductance	5 μH
Signal inductance Q	160
Characteristic impedance	317 Ω
Idler frequency	800 MHz
Pump frequency	830 MHz
Single-stage noise figure	0.25 dB
Multistage noise figure at high overall gain	0.34 dB

idler circuit (the capacitance C_I in series with inductance L_I) gives a total shunt capacitance of 15.5 pF. R_d is 0.7 Ω.

The design parameters are summarized in Table I; gain and noise figure have been calculated from the appropriate expressions in [1].

$$\text{Loss} = \frac{\left[R_d^2 + \left(\frac{1}{\omega_s C_0}\right)^2\right] 4Z_0^2}{\left|\left(Z_0 + \frac{1}{2}R_s\right)^2 + \left(\frac{\omega_s L}{2}\right)^2\right| \left\{\left(Z_0 + \frac{R_s}{2} + 2R_d\right)^2 + \frac{4}{\omega_s^2 C_0^2}\left(1 - \frac{\omega_s^2 L C_0}{4}\right)^2\right\}}.$$

The signal circuit inductance consists of some 8 turns of 22 standard wire gauge (SWG) enameled copper wire mounted on an air cored former. The Q of each 1/2 section (2.5 μH) was measured to be 160.

The parallel resonant filters C_f and L_f are tuned midway between the pump and the idler frequency. L_f is a single turn inductor and C_f is an air spaced 5-pF maximum variable capacitor (Tekelec-Gigatrim).

The pump series capacitor is 0.4 pF.

III. Amplifier Performance

B. *Characteristic Impedance*

The characteristic impedance of the T section was measured by terminating the T section in a variable resistor and adjusting this so that the real component of the input impedance of the T section was equal to the resistance load, thereby giving the characteristic impedance. Both impedances were measured on a VHF admittance bridge.

The measured value of the characteristic impedance at 30 MHz was 315 Ω. The calculated value, using (3) is 318 Ω with C_0 equal to 15.5 pF and L equal to 5 μH.

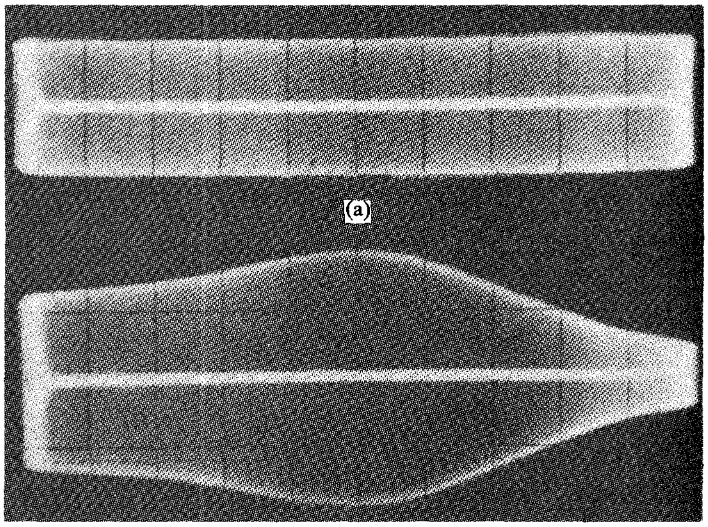
C. *Passive Insertion Loss*

The insertion loss of the passive T section was measured at 30 MHz using a vector voltmeter (HP 8405A) and compared with the theoretical expression from [1] which is

Fig. 7 shows the measured and calculated insertion loss as a function of frequency. At 30 MHz the measured insertion loss is 0.18 dB and the calculated insertion loss is 0.176 dB.

D. *Gain-Frequency Response*

The gain was measured with a 75-Ω sweeper. Series resistors were added so that the source and load imped-



(b)

Fig. 8. Photograph showing the input and output of the amplifier as a function of frequency. (a) Input sweep from 25 to 35 MHz. (b) Output.

ances became 315 Ω thus giving matched conditions. Input and output voltages were measured with a double beam oscilloscope across the source and load. Fig. 8 shows the oscilloscope display at the amplifier input and output, sweeping from 25 to 35 MHz, giving a 5-dB gain and 3-dB bandwidth of 6 MHz. The gain as a function of frequency is observed to be asymmetrical and a typical result is shown in Fig. 9.

Theoretical gain is calculated from the expression

$$G_{av}=\frac{1+\left(\frac{\omega_s C_0 Z_0}{2}\right)^2}{\left[1+\left(\frac{\omega_s L}{2Z_0}\right)^2\right]\left(1-\frac{\omega_s^2 L C_0}{4}\right)^2}.$$

The maximum gain obtainable was measured with a range of signal circuit inductances and compared with the theoretical gain. The result of this comparison is given in Fig. 10, showing a maximum discrepancy between measurement and theory of 0.3 dB.

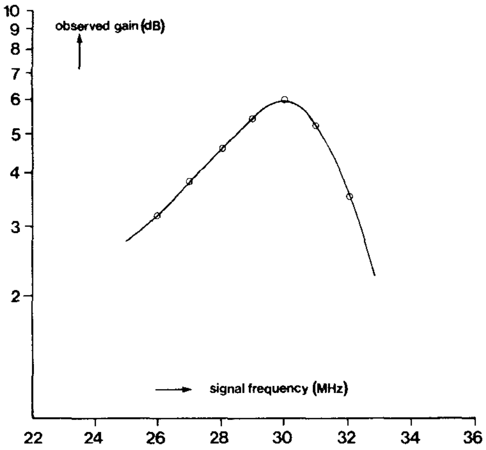


Fig. 9. Observed gain as a function of frequency.

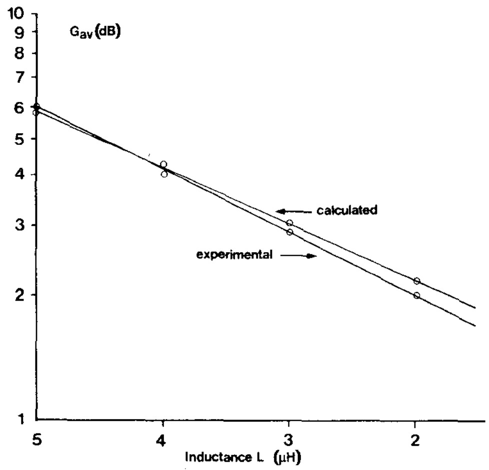


Fig. 10. Theoretical and experimental observed gain as a function of the inductance L.

E. Gain Dependence on Pump Power

The expression [1] for load current I_L is

$$I_L^2=\frac{E^2\left[(R_d-R_n)^2+\left(\frac{1}{\omega_s C_0}\right)^2\right]}{\left[\left(Z_0+\frac{1}{2}R_s\right)^2+\left(\frac{\omega_s L}{2}\right)^2\right]\left[\left(Z_0+\frac{1}{2}R_s+2R_d-2R_n\right)^2+\frac{4}{\omega_s^2 C_0^2}\left(1-\frac{\omega_s^2 L C_0}{4}\right)^2\right]}$$

where

$$R_n=\frac{\gamma^2}{C_0^2\omega_s\omega_I R_d}.$$

Examination of this expression shows that the gain should reach a maximum with increase of pump power—when $(Z_0+1/2R_s+2R_d-2R_n)$ equals zero—and should decrease with further increase in pump power.

The theoretical variation of gain with pump power is given by the continuous line in Fig. 11. The measured points are plotted. It will be seen that the measured gain peaks at a particular pump power and then falls away monotonically. This is a significant result since it means that the individual hybrid parametric amplifier stage cannot oscillate as a result of pump power change, unlike the conventional resonant parametric amplifier. A cascade of hybrid amplifiers can oscillate if an appropriate combination of mismatches are provided at both the input and output. An isolator between the final stage and output load will prevent this form of oscillation without noise figure penalty.

F. Noise Figure Performance

1) Single-Stage Amplifier: The noise figure of a single-stage hybrid parametric amplifier was measured using a shot noise thermionic diode in conjunction with a

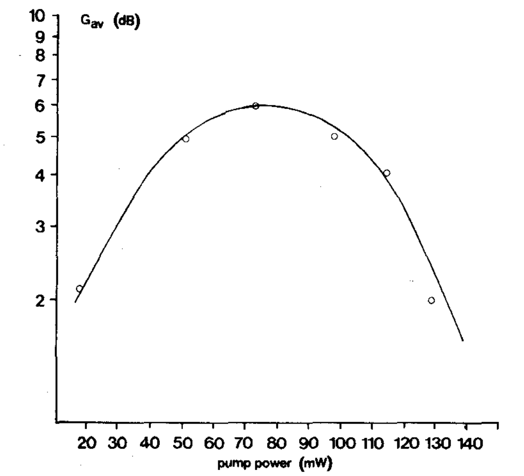


Fig. 11. Observed variation of gain with pump power.

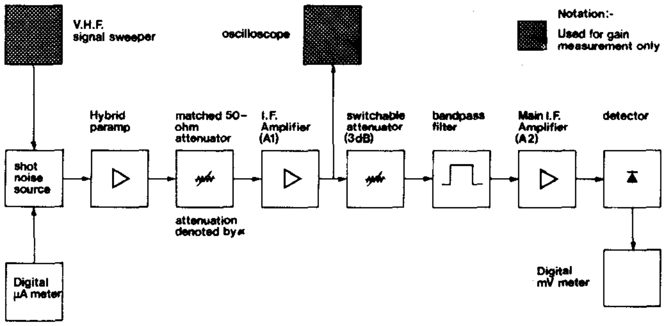


Fig. 12. Experimental arrangement for the measurement of the hybrid parametric amplifier noise figure.

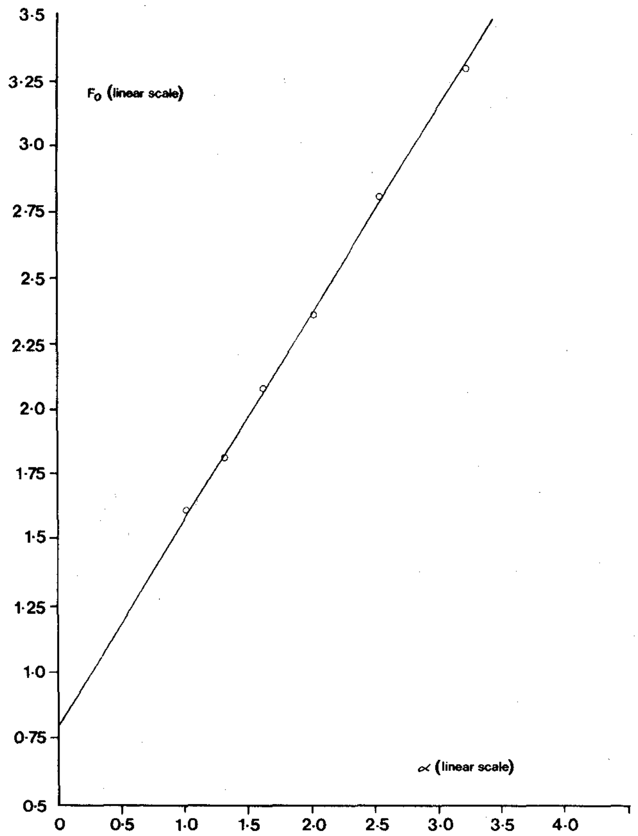


Fig. 13. Plot of overall noise figure F_0 against α for single-stage hybrid parametric amplifier with signal inductor $Q = 160$.

following IF amplifier of high gain and a calibrated attenuator. The experimental arrangement is shown in Fig. 12.

It will be seen that a suitable 50-Ω attenuator is situated between the hybrid parametric amplifier and the following system. The overall noise figure of the combination is measured as a function of α, the attenuation factor of the attenuator.

The overall noise figure of the system F_0 is given in terms of the hybrid amplifier noise figure F_1, its available gain G_{av}, and the noise figure of the amplifier system following the attenuator F_2, by the expression

$$F_0 = F_1 + \frac{\alpha - 1}{G_{av1}} + \frac{F_2 - 1}{G_{av1}\left(\frac{1}{\alpha}\right)}$$

so that

$$F_0 = \left(F_1 - \frac{1}{G_{av1}}\right) + \frac{\alpha F_2}{G_{av1}}.$$

Thus a plot of F_0 against α is a straight line of intercept $F_1 - (1/G_{av1})$ and slope F_2/G_{av1}. F_0 is obtained from the intercept by using the *in-situ* measured value of G_{av} obtained with the sweeper and oscilloscope shown in Fig. 12. This value of G_{av} is checked by using the slope of the graph and the previously measured value of F_2.

A bandpass filter of bandwidth 6 MHz is placed between the two main IF amplifiers to restrict the bandwidth of the measurement system to a value similar to that of the hybrid parametric amplifier.

The output impedance of the hybrid parametric amplifier is transformed to 50 Ω with a tapped 30-MHz resonant circuit. The correct tap position is found by measuring the input admittance with a bridge.

Fig. 13 shows the plot of F_0 against α using T-section inductances with a Q of 160. The noise figure of the hybrid parametric amplifier obtained from this graph is 1.062 (0.26 dB) or a noise temperature of 18 K.

In order to compare theory with practice the Q of the T-section inductances were then artificially degraded by adding series resistors. The noise figure of the hybrid parametric amplifier was measured by the same technique and the Q of the inductances measured with a Q meter. A table of measured hybrid parametric amplifier noise figures as a function of inductance Q is shown in Table II. Shot noise diode current was measured to an accuracy of

TABLE II
COMPARISON BETWEEN CALCULATED AND MEASURED NOISE FIGURE FOR DIFFERENT INDUCTOR Q VALUES[a]

	calculated noise figure F_1			Measured noise figure F_1		
Q Inductor	F_1	F_1(dB)	F_1(K)	F_1	F_1(dB)	F_1(K)
160	1.059	0.25	17	1.062	0.26	18
90	1.069	0.29	20	1.074	0.31	22
55	1.084	0.35	24	1.086	0.36	25
30	1.114	0.47	33	1.125	0.51	36

[a]Accuracy: −0.02 dB for 1-μA accuracy in measuring diode current.

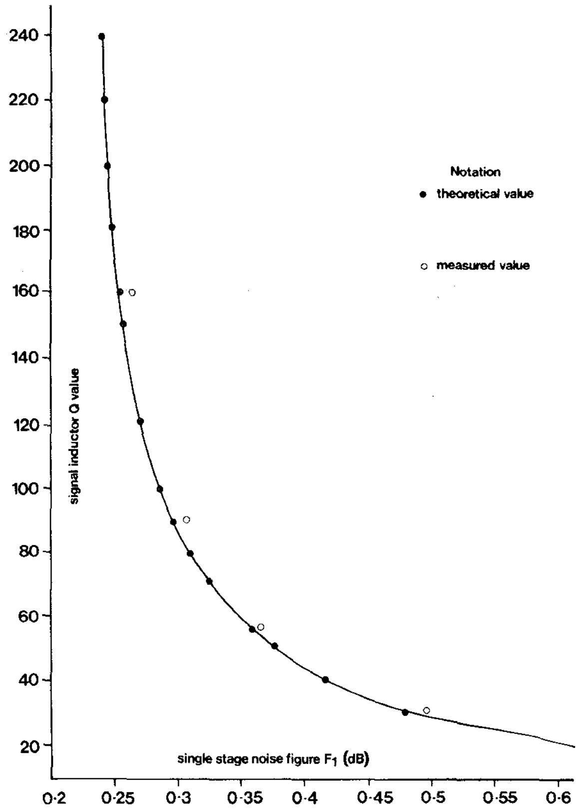


Fig. 14. Graph showing theoretical and measured single-stage noise figure F_1 of the hybrid parametric amplifier as a function of signal inductor Q values.

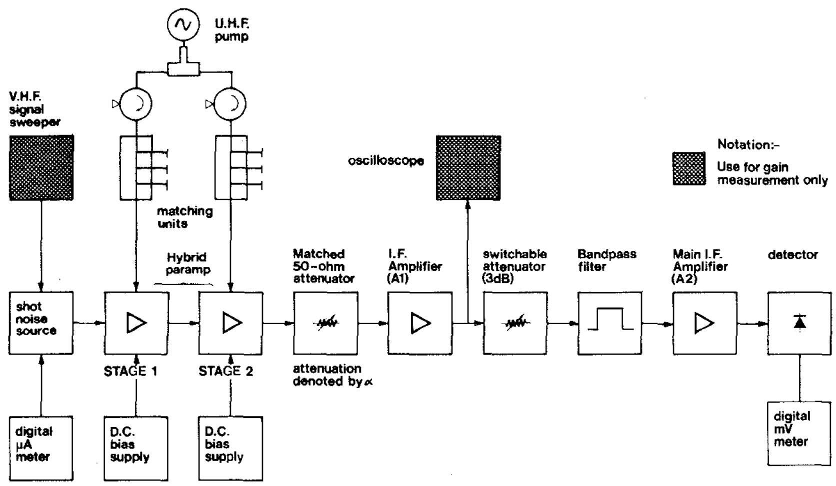


Fig. 15. Two-stage hybrid parametric amplifier noise figure measurement.

1 μA giving a corresponding noise figure accuracy of 0.02 dB.

The theoretical noise figure was obtained by using the expression [1]

$$F_1 = 1 + \frac{2}{q}\left[\frac{1-g(1-g)}{1+g(1+g)}\right] + \frac{2g}{1+g(1-g)}\left[\frac{1}{p} + \frac{f_s}{f_I}\left(1+\frac{1}{p}+\frac{1}{q}\right)\right]$$

where

$$g^2 = \frac{\omega_s^2 L C_0}{4}$$

$$p = \frac{Z_0}{2R_d}$$

$$q = \frac{Z_0}{\frac{1}{2}R_s}.$$

Table II also shows the theoretical noise figure as a

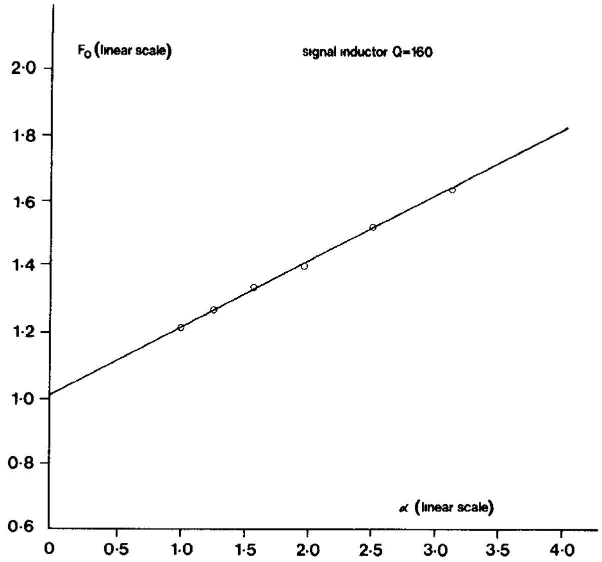


Fig. 16. F_0 versus α for two stage hybrid parametric amplifier.

function of Q. The agreement between the two is close as can be seen from Fig. 14 in which both the experimental and calculated noise figures are plotted against Q.

2) Two-Stage Amplifier: The noise figure was confirmed by cascading two hybrid parametric amplifier stages both identical to the single stage described above. The arrangement is shown in Fig. 15. Again the noise diode was provided with a resistance equal to the Z_0 of the amplifier and a transformer from 315 Ω to 50 Ω was provided at the output of the second stage. A common pump source was used for both stages.

A plot of overall noise figure against α is shown in Fig. 16 for this arrangement. The noise figure obtained from the intercept was 0.266 dB for this combination.

G. Noise Measure

The noise performance of an amplifier of moderate gain is best expressed in terms of noise measure M. This is defined by the expression

$$M=\frac{F-1}{1-\dfrac{1}{G_{av}}}.$$

A cascaded arrangement of n identical amplifiers has a noise figure F given by

$$F=1+M\left[1-\left(\frac{1}{G_{av}}\right)^n\right]$$

where G_{av} is the available gain of a single stage. This excess noise figure $(F-1)$ of a system of n identical stages limits to M as n becomes large.

The expression for noise measure for the hybrid parametric amplifier is given by

$$M=\frac{2}{p}\left[\frac{1-g(1-g)}{g(2-g)}\right]+\frac{2}{(2-g)}\left[\frac{1}{p}+\frac{f_s}{f_I}\left(1+\frac{1}{p}+\frac{1}{q}\right)\right].$$

TABLE III
SHOWING THE COMPUTED VALUES OF M AND F_n FOR DIFFERENT MEASURED VALUES OF THE SINGLE-STAGE NOISE FIGURE F_1 AT CONSTANT GAIN (6 dB) OF THE HYBRID PARAMETRIC AMPLIFIER, OBTAINED WITH VARIOUS SIGNAL INDUCTOR Q'S

Inductor Q	Measured F_1			Calculated M and F_n			
	F_1	F_1(dB)	F_1(K)	M	F_n	F_n(dB)	F_n(K)
160	1.062	0.26	18	0.0822	1.082	0.34	24
90	1.074	0.31	22	0.0986	1.099	0.41	29
55	1.086	0.36	25	0.1152	1.115	0.47	33
30	1.125	0.51	36	0.1661	1.166	0.67	48

The noise measure and noise figure for n identical stages have been calculated using the single-stage noise figure and available gain measurements. These are tabulated in Table III for various inductance Q's.

The noise measure corresponding to the measured single-stage noise figure of 1.062 (0.26 dB) or 18 K noise temperature is 0.0822 which gives a noise figure for a large number of identical stages of 1.082 (0.34 dB) or 24 K noise temperature.

3) Minimum Noise Measure: Since both noise figure and available gain of the hybrid parametric amplifier are functions of g we may expect an optimum value of g corresponding to a minimum value of M. The value of M has been investigated by computing M while allowing L and C_0 to vary. This has been done in three ways.

1) M is computed for different values of L with C_0 kept constant.

2) M is computed for different values of C_0 with L kept constant.

3) M is computed as both L and C_0 vary.

a) Variation of M by changing L with C_0 fixed. C_0 is fixed at 15.5 pF and associated R_d at 0.7 Ω. The calculated noise measure at 30 MHz is shown in Fig. 17 and shows a minimum at an inductance value of approximately 2 μH. The minimum value of M is 0.068 corresponding to a noise figure for n stages giving a total of 20-dB gain of

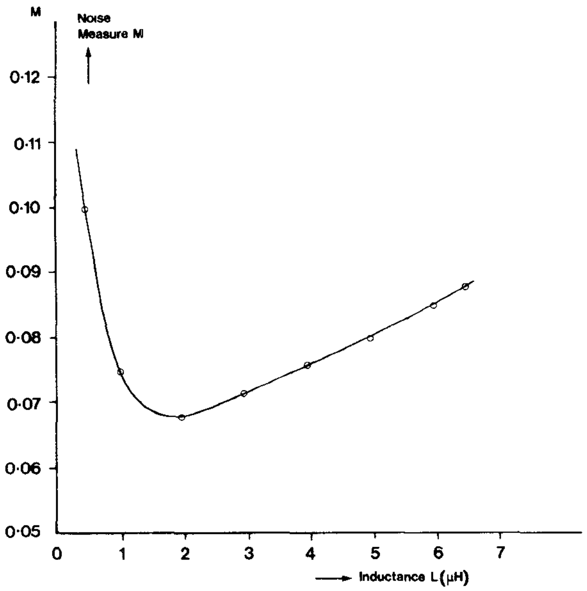


Fig. 17. Theoretical noise measure M as a function of signal inductance L for $C=15.5$ pF, $R_d=0.7\ \Omega$ for the hybrid parametric amplifier at 30 MHz.

1.068 or a noise temperature of 20 K. The stage gain is 2.2 dB and the idling frequency is 870 MHz.

b) Variation of M by changing C_0 with L fixed. L is fixed at 5 μH with a Q of 160. The calculated noise measure at 30 MHz shows a minimum at a capacitance of approximately 2.8 pF. The minimum value of M is 0.025 corresponding to a noise figure (for n stages giving a total of 20-dB gain) of 1.025 or a noise temperature of 7.05 K. The stage gain is 1.1 dB and the idling frequency is 6 GHz.

c) Variation of M by changing C_0 and L. An optimization routine can be used to optimize both L and C_0 together. This shows that the noise measure can be made to approach zero as L is increased and C_0 decreased and g is decreased, thereby increasing Z_0 and the idling frequency.

In practice, the cost of microwave pumps and the inconvenience of using high values of Z_0 determine the noise measure limit in a given situation.

IV. Conclusions

It is concluded that the hybrid parametric amplifier is viable and that gain and noise performance are in accordance with theory.

Of particular note is the noncritical dependence of gain on pump power.

A 30-MHz hybrid parametric amplifier with 6-dB gain and 6-MHz bandwidth has been built and has a noise temperature of 18 K corresponding to a noise measure of 0.082.

References

[1] C. S. Aitchison and A. Wong, "The hybrid parametric amplifier," pp. 833–839, this issue.