The Intrinsic Noise Figure of the MESFET Distributed Amplifier

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Abstract—This paper calculates the intrinsic noise figure of the MESFET distributed amplifier assuming, for simplicity, only the Van der Ziel gate and drain noise sources, and produces an expression for the noise figure of a distributed amplifier containing n identical devices. For large gain and large n, a simple expression exists for the product $nZ_{\pi g}$, where $Z_{\pi g}$ is the π-characteristic impedance of the gate line, which minimizes the overall noise figure of the amplifier.

This approximate expression is compared with the corresponding expression for a resonant amplifier using the same MESFET with the same noise sources and with the optimum source impedance for minimum noise figure. Although the resonant amplifier has a slightly lower noise figure, the need to use a circulator to remove the mismatch associated with the optimum source impedance removes this slight advantage.

I. Introduction

THE DISTRIBUTED amplifier was first proposed in 1936 by Percival [1] as an attempt to produce an amplifier without the usual gain–bandwidth constraint implicit in a resonant amplifier using a given active device, and is determined by the relevant physical parameters of that device. Several workers exploited this idea with thermionic devices [2].

More recently, interest has arisen in the performance of microwave distributed amplifiers using MESFET's [3], [4]. Niclas and Tucker [5] consider the noise figure of the distributed amplifier using matrix techniques involving a four-port representation in matrix form.

This paper considers the intrinsic noise figure of the MESFET distributed amplifier and, therefore, assumes that the only noise sources present are the two current generators postulated by Van der Ziel. A simple calculation leads to an expression for the noise figure in terms of known parameters of the device, and it is shown that, for high values of n (the number of stages), there is an optimum value of the gate characteristic impedance which yields a minimum intrinsic noise figure for the distributed amplifier. This figure is compared with the corresponding noise figure for a resonant MESFET amplifier in which the source impedance is optimized to give the minimum noise figure.

The noise figure of the distributed amplifier is of particular interest since this form of amplifier has an unusual signal-to-noise behavior. Consider an n-stage distributed amplifier to which a further stage is added at the output.

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The additional signal voltage produced by this $(n+1)$th stage will, if the circuit conditions are correct, add linearly with the output voltage due to the prior n stages, while the noise from this additional stage will add quadratically to the noise from the previous stages. Thus, the effect of the additional stage is to improve the signal-to-noise ratio corresponding to a reduction in noise figure. This agreement suggests that the noise figure of the distributed amplifier will decrease as the number of stages is increased. A detailed calculation of the noise figure is required to establish the validity of this conclusion.

This argument is not in contradiction to the Friis noise-figure cascading expression [6], and this expression applies to a cascade of two or more distributed amplifiers. The noise figure of such a cascade arrangement does not decrease as the number of cascaded amplifiers increases.

II. Available Gain of a Distributed Amplifier

In order to calculate the noise figure, we need expressions for the available gain of a distributed amplifier with MESFET's as the active device. We assume, for convenience, the simple MESFET equivalent circuit shown in Fig. 1. Essentially, the MESFET is considered to be loss-free and to consist of a gate capacitance C_{gs} and a drain current generator with associated drain capacitance C_{ds}. Other elements in the more general equivalent circuit are neglected.

Similarly, the artificial transmission lines which form the gate line and drain line are considered to be formed from loss-free lumped components. Such an arrangement with grounded source MESFET's is illustrated in Fig. 2. The gate- and drain-line characteristic impedances are $Z_{\pi g}$ and $Z_{\pi d}$, respectively, and the two lines are terminated in characteristic impedances. The left-hand gate-line termination is a generator E_s with impedance $Z_{\pi g}$.

It is clear that a wave from the gate generator propagates down the gate line with a phase constant β_g per section and is entirely dissipated in the right-hand gate load. The voltage across each gate capacitor produces a current generator $g_m V_g$ in the drain line, and the current from each generator flows in both directions with phase constant β_d per section. Thus, power will be dissipated in both the drain loads, and we can calculate an available gain for the right-hand drain load (forward gain) and the left-hand drain load (reverse gain). We deal with the forward available gain first.

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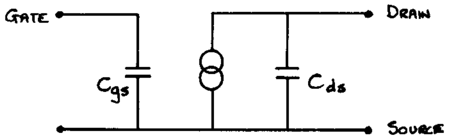

Fig. 1. Simple MESFET equivalent circuit.

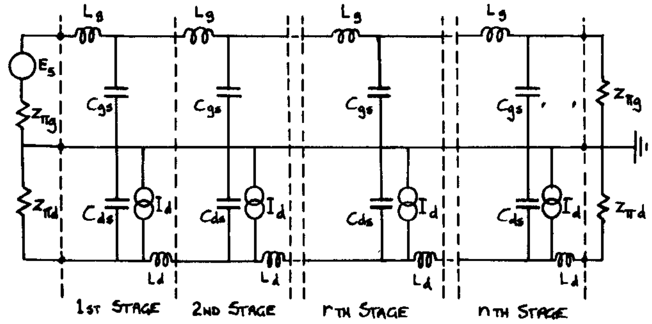

Fig. 2. Distributed MESFET amplifier with n sections.

It is convenient both for the calculation of gain (and later noise figure) to analyze the distributed amplifier in terms of π-sections since $Z_{\pi d}$ appears both to the left and to the right of each drain current generator.

A. Forward Available Gain

We first consider that the current generators have a magnitude $I_1, I_2, \cdots, I_n$, etc. Since superposition applies, the total current I_d in the load $Z_{\pi d}$ is given by

$$I_d = \frac{1}{2}\left\{ I_1 e^{-jn\beta_d} + I_2 e^{-j(n-1)\beta_d}, \cdots, I_n e^{-j\beta_d} \right\}. \quad (1)$$

The voltage wave traveling down the gate line due to E_s produces voltages $V_1, V_2, \cdots, V_n$ across each gate capacitor where $V_1, V_2, \cdots, V_n$ are related to V_{in}, where V_{in} is the voltage across the input terminals of the gate line, by the expressions

$$V_1 = V_{\text{in}} e^{-j\beta_g}, V_2 = V_{\text{in}} e^{-2j\beta_g}, \cdots, V_n = V_{\text{in}} e^{-nj\beta_g}. \quad (2)$$

We know that

$$I_1 = g_m V_1, I_2 = g_m V_2, \cdots, I_n = g_m V_n. \quad (3)$$

Since we have assumed the gate line to be loss-free, we can write

$$|V_1| = |V_2| = |V_n| = |V_{\text{in}}|. \quad (4)$$

It follows from (3) and (4) that

$$|I_1| = |I_2| = |I_n| = |I|. \quad (5)$$

Substituting (3), (4), and (5) into (1) and (2) yields

$$I_d = \frac{1}{2} V_{\text{in}} g_m \cdot \left\{ e^{-j(n\beta_d + \beta_g)} + e^{-j((n-1)\beta_d + 2\beta_g)} + \cdots + e^{-j(\beta_d + n\beta_g)} \right\} \quad (6)$$

$$= \frac{1}{2} V_{\text{in}} g_m e^{-j(n\beta_d + \beta_g)} \cdot \left\{ 1 + e^{-j(\beta_g - \beta_d)} + e^{-2j(\beta_g - \beta_d)} + \cdots + e^{-(n-1)j(\beta_g - \beta_d)} \right\} \quad (7)$$

$$= \frac{1}{2} V_{\text{in}} g_m \left\{ \frac{1 - e^{jn(\beta_d - \beta_g)}}{1 - e^{j(\beta_d - \beta_g)}} \right\} e^{-j(n\beta_d + \beta_g)}. \quad (8)$$

But V_{in} is equal to $\frac{1}{2}E_s$ for a matched line, so (8) can be written as

$$|I_d| = \frac{1}{4} E_s g_m \left| \frac{\sin \frac{n}{2}(\beta_d - \beta_g)}{\sin \frac{1}{2}(\beta_d - \beta_g)} \right|. \quad (9)$$

The power dissipated in the load $Z_{\pi d}$ is

$$\frac{E_s^2}{16} g_m^2 \left(\frac{\sin \frac{n}{2}(\beta_d - \beta_g)}{\sin \frac{1}{2}(\beta_d - \beta_g)} \right)^2 Z_{\pi d}. \quad (10)$$

The power available from the generator is $E_s^2/4Z_{\pi g}$, so that the forward available gain G_f is given by the expression

$$G_f = \frac{g_m^2 Z_{\pi d} Z_{\pi g}}{4} \left(\frac{\sin \frac{n}{2}(\beta_d - \beta_g)}{\sin \frac{1}{2}(\beta_d - \beta_g)} \right)^2. \quad (11)$$

This expression becomes independent of frequency if $(\beta_d - \beta_g)$ equals zero, and then

$$G_f = \frac{n^2 g_m^2 Z_{\pi g} Z_{\pi d}}{4}. \quad (12)$$

Note that if the gate- and drain-line cutoff frequencies are made sufficiently high, then $Z_{\pi g}$ and $Z_{\pi d}$ can be replaced by Z_{0g} and Z_{0d},[1] both of which are frequency independent. There is then no restriction, in principle, on the gain–bandwidth product, and the gain can be increased indefinitely by increasing n while the bandwidth remains constant, though this applies only in the loss-free case.

B. Reverse Available Gain

We wish to calculate the available gain G_r for power dissipated in the left-hand drain load. The current flowing through the left-hand drain load is given by

$$I_d = \frac{1}{2}\left\{ I_1 + I_2 e^{-j\beta_d} \cdots + I_n e^{-(n-1)j\beta_d} \right\}. \quad (13)$$

The relationships given by (2), (3), (4), and (5) apply, so we can write

$$I_d = \frac{1}{2} V_{\text{in}} g_m \left\{ e^{-j\beta_g} + e^{-j(2\beta_g + \beta_d)} + \cdots e^{-j(n\beta_g + (n-1)\beta_d)} \right\} \quad (14)$$

$$= \frac{1}{2} V_{\text{in}} g_m \left\{ \frac{1 - e^{jn(\beta_g + \beta_d)}}{1 - e^{j(\beta_g + \beta_d)}} \right\} e^{-j\beta_g}. \quad (15)$$

But V_{in} is equal to $\frac{1}{2}E_s$ for a matched line, so (15) can be written as

$$|I_d| = \frac{1}{4} E_s g_m \left| \frac{\sin \frac{n}{2}(\beta_g + \beta_d)}{\sin \frac{1}{2}(\beta_g + \beta_d)} \right|. \quad (16)$$

[1] Z_0 refers to $\sqrt{\frac{L}{C}}$, where L and C are the appropriate gate- and drain-line inductances and capacitances.

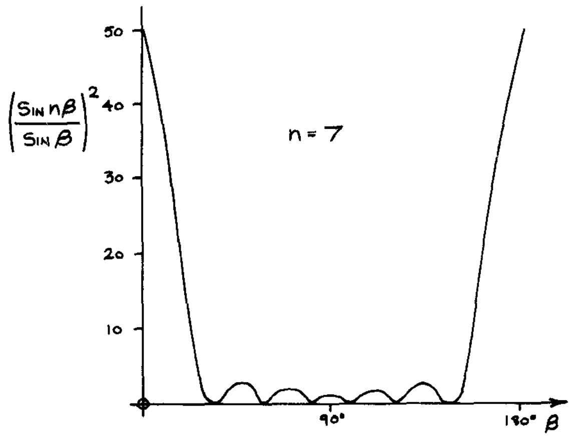

Fig. 3. Graph of $(\sin n\beta/\sin\beta)^2$ as a function of β for $n = 7$.

The power dissipated in the load $Z_{\pi d}$ is

$$\frac{E_s^2 g_m^2}{16}\left(\frac{\sin\frac{n}{2}(\beta_g+\beta_d)}{\sin\frac{1}{2}(\beta_g+\beta_d)}\right)^2 Z_{\pi d} \tag{17}$$

and the reverse available gain is given by

$$G_r = \frac{g_m^2 Z_{\pi d} Z_{\pi g}}{4}\left(\frac{\sin\frac{n}{2}(\beta_g+\beta_d)}{\sin\frac{1}{2}(\beta_g+\beta_d)}\right)^2. \tag{18}$$

But for maximum forward gain, β_d equals β_g (which we write as β); then (18) becomes

$$G_r = \frac{g_m^2 Z_{\pi d} Z_{\pi g}}{4}\left(\frac{\sin n\beta}{\sin\beta}\right)^2. \tag{19}$$

The function $(\sin n\beta/\sin\beta)^2$ is a well-known function and is sketched in Fig. 3. It can be seen that the value of the function is small except when $n\beta$ is close to zero or π when the function approaches n^2 and the forward and reverse available gains are identical.

We conclude that the forward gain can be made as large as is required simply by increasing n while the reverse gain becomes negligible except at those frequencies at which $n\beta$ is close to zero or π.

III. Noise Figure of Distributed Amplifier

The noise-figure definition [7] requires that noise powers available to or dissipated in the load be calculated. The intrinsic noise sources can be identified as

1) noise from the gate source impedance ($Z_{\pi g}$), which, in accordance with the noise-figure definition, is at the standard temperature T_0,
2) noise from the gate load ($Z_{\pi g}$), which we will assume is at T_0,
3) noise from the left-hand drain load ($Z_{\pi d}$), which we will assume is at T_0,
4) noise associated with each of the n FET's.

The noise associated with the right line drain load ($Z_{\pi d}$) does not contribute to the distributed amplifier noise figure since it is part of the following network. We treat these noise sources in sequence.

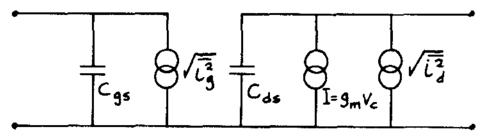

Fig. 4. Equivalent circuit of MESFET showing gate $\left(\sqrt{\overline{i_g^2}}\right)$ and drain $\left(\sqrt{\overline{i_d^2}}\right)$ noise generators.

A. *Noise from Gate Source Impedances and Left-Hand Drain Load*

The noise power available from the source impedance $Z_{\pi g}$ at the standard temperature is kT_0B. The noise power dissipated in the right-hand drain load is $G_f kT_0 B$, which is given by

$$kT_0B\cdot\frac{n^2 g_m^2 Z_{\pi g} Z_{\pi d}}{4}. \tag{20}$$

The noise power available from the gate load is kT_0B. The noise power dissipated in the right-hand drain load is $G_r kT_0 B$, which is given by

$$kT_0B\frac{g_m^2 Z_{\pi g} Z_{\pi d}}{4}\left(\frac{\sin n\beta}{\sin\beta}\right)^2. \tag{21}$$

The noise power available from the left-hand drain load (since the drain line is assumed to be loss-free) is given by

$$kT_0B. \tag{22}$$

B. *Noise Associated with the FET's*

Van der Ziel and others [8], [9] have suggested that the FET noise behavior can be represented by a gate current generator $\sqrt{\overline{i_g^2}}$ and a drain current generator $\sqrt{\overline{i_d^2}}$ together with a complex correlation coefficient. One current generator, $\sqrt{\overline{i_g^2}}$, is placed in shunt with the gate capacitance and the second, $\sqrt{\overline{i_d^2}}$, is placed in shunt with the drain capacitance as shown in Fig. 4. The mean square values of i_g and i_d are given by

$$\overline{i_g^2} = 4kT_0B\frac{\omega^2 C_{gs}^2}{g_m}R \quad \text{and} \quad \overline{i_d^2} = 4kT_0Bg_mP \tag{23}$$

where R and P are numerical factors which vary with drain current and are plotted in [10].

The correlation coefficient C is complex and is equal to $C_r + jC_{im}$. Van der Ziel [9] has shown that C_r is zero and C_{im} is about 0.35, but again depends upon drain current [10].

1) Noise Contribution due to rth Stage MESFET: We now consider the noise contribution from the rth stage of the n stage amplifier. Noise from the rth stage gate current generator is dissipated in the right-hand drain load both by forward amplification in the succeeding stages and also by reverse amplification occurring in the earlier stages. To the vector resultant of these two gain mechanisms has to be added the drain contribution from the rth stage taking into

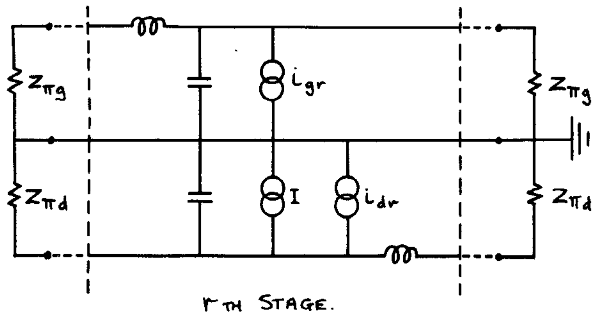

Fig. 5. Noise sources associated with the rth stage of the distributed amplifier.

account the correlation between the gate and drain generators. The noise generators associated with the rth stage are shown in Fig. 5.

We first consider the current through the drain load due to the rth gate generator.

The current $I_d(r)$ through the drain load due to the rth gate generator i_{gr} due to forward amplification is given by

$$I_d(r)=\frac{1}{2}\left\{I_r e^{-j(n-r+1)\beta_d}+I_{r+1}e^{-j(n-r)\beta_d}+\cdots+I_n e^{-j\beta_d}\right\} \tag{24}$$

where I_r, I_{r+1}, etc., are the current generators in the drain line at the rth, $(r+1)$th, etc., stages, respectively. But

$$I_r=\frac{1}{2}g_m i_{gr} Z_{\pi g}$$

$$I_{r+1}=\frac{1}{2}g_m i_{gr} Z_{\pi g} e^{-j\beta_g}$$

$$I_n=\frac{1}{2}g_m i_{gr} Z_{\pi g} e^{-j(n-r)\beta_g} \tag{25}$$

where i_{gr} is used to represent its rms value $\sqrt{\overline{i_{gr}^2}}$. Substituting (25) into (24) gives

$$I_d(r)=\frac{1}{4}g_m i_{gr} Z_{\pi g} \cdot\left\{e^{-j(n-r+1)\beta_d}+e^{-j(n-r)\beta_d}e^{-j\beta_g}\cdots+e^{-j\beta_d}e^{-j(n-r)\beta_g}\right\}. \tag{26}$$

But for maximum gain, $\beta_g=\beta_d=\beta$, and (26) becomes

$$I_d(r)=\frac{1}{4}g_m i_{gr} Z_{\pi g}(n-r+1)e^{-j(n-r+1)\beta}. \tag{27}$$

The current through the drain load due to the rth gate generator i_{gr} due to reverse amplification $I_d(r)$ is given by

$$I_d(r)=\frac{1}{4}g_m i_{gr} Z_{\pi g} e^{-j(n-r+1)\beta_d} \cdot\left\{e^{-j(\beta_d+\beta_g)}+e^{-2j(\beta_d+\beta_g)}+e^{-j(r-1)(\beta_d+\beta_g)}\right\}. \tag{28}$$

Again, for maximum gain, $\beta_g=\beta_d=\beta$, and (28) becomes

$$I_d(r)=\frac{1}{4}g_m i_{gr} Z_{\pi g}\left(\frac{\sin(r-1)\beta}{\sin\beta}\right)e^{-j(n+1)\beta}. \tag{29}$$

The total current in the drain load due to the rth section gate current generator $I_d'(r)$ is obtained by combining (27) and (29) vectorially to give

$$|I_d'(r)|^2=\left(\frac{1}{4}g_m i_{gr} Z_{\pi g}\right)^2 \cdot\left\{(n-r+1)^2+\left(\frac{\sin(r-1)\beta}{\sin\beta}\right)^2+\frac{2(n-r+1)\sin(r-1)\beta\cos r\beta}{\sin\beta}\right\}. \tag{30}$$

It is convenient to represent the second parenthesis term $\{\ \}$ by the symbol $f(r,\beta)$.

The current through the drain load due to the rth section drain generator is given by $\frac{1}{2}i_d$. To combine this with $I_d'(r)$ of (30), we have to take into account the partial correlation between i_{rg} and i_{rd}. Both i_{rg} and i_{rd} feed impedances which are purely real, and the complex correlation coefficient has a zero real part so that there is no correlation contribution to the power dissipated in the load.

The total power dissipated in the drain load due to gate and drain current generators is obtained by combining (30) with $\frac{1}{2}i_d$ to give the expression

$$\left\{\left(\frac{1}{4}g_m^2 i_{gr} Z_{\pi g}\right)^2 f(r,\beta)+\left(\frac{1}{2}i_d\right)^2\right\}Z_{\pi d}. \tag{31}$$

2) Noise Contribution from the n MESFET's: The noise power dissipated in the drain load from the n MESFET's can be obtained by summing (31) over n since noise from one FET is uncorrelated with that from its neighbors. The summed noise power is given by the expression

$$\left\{\left(\frac{1}{4}g_m i_g Z_{\pi g}\right)^2\sum_{r=1}^{n} f(r,\beta)+\frac{1}{4}n i_d^2\right\}Z_{\pi d}. \tag{32}$$

The expressions (23) can be substituted into (32) to give

$$4kT_0B\left\{\left(\frac{1}{4}g_m Z_{\pi g}\right)^2\frac{\omega^2 C_{gs}^2}{g_m}R\sum_{r=1}^{n} f(r,\beta)+\frac{1}{4}n g_m P\right\}Z_{\pi d}. \tag{33}$$

C. Noise Figure

Using the definition of noise figure F and (20), (21), (22), and (33), we can write

$$F=1+\left(\frac{\sin n\beta}{n\sin\beta}\right)^2+\frac{4}{n^2 g_m^2 Z_{\pi g} Z_{\pi d}}+\frac{Z_{\pi g}\omega^2 C_{gs}^2 R\sum_{r=1}^{n} f(r,\beta)}{n^2 g_m}+\frac{4P}{n g_m Z_{\pi g}}. \tag{34}$$

It is helpful to examine (34) term by term. The second term is small for large n except when $n\beta$ is close to 0 or π when the expression has a maximum value of unity. For other phase angles, the term can be as small as is required by increasing n. The third term is the reciprocal of the forward available gain and can be made as small as is required by increasing n. The fourth term (which is due to

TABLE I
ASSUMED MESFET EQUIVALENT-CIRCUIT VALUES USED TO COMPUTE FIG. 6

$Z_{\pi g}$ (Ω)	50
C_{gs} (pF)	0.5
C_{ds} (pF)	0.2
g_m (S)	30.10^{-3}
R	0.2
P	0.6

the gate generators) contains a summation which is defined by (30). The first term of (30) is the most significant for large n and is equal to $\Sigma_{r=1}^{n} r^2$ and sums to $n/6(n+1)(2n+1)$ which limits to $n^3/3$. Thus, the gate generator contribution to (34) is proportional to n. The final term of (34) (which is due to the drain generators) is inversely proportional to n and can be made negligible by increasing n.

We conclude that for large n (such that the first 2 non-unity terms of (34) are negligible) there exists an optimum value of n such that the contributions from the fourth and fifth terms are identical.

IV. PREDICTED NOISE FIGURE

Equation (34) enables the variation of noise figure with frequency to be plotted with n as a parameter for assumed values of the parameters $Z_{\pi g}$, C_{gs}, C_{ds}, g_m, R, and P. It is necessary to arrange that β_g is equal to β_d, and thus the cutoff frequency of the gate and drain lines varies with the value of $Z_{\pi g}$. Similarly, the value of $Z_{\pi d}$ is determined by the phase relationship. The relevant artificial transmission-line expressions for Z_π and β are

$$Z_\pi = \left\{ \frac{L/C}{1-(\omega/\omega_c)^2} \right\}^{1/2}$$

and

$$\beta = 2\sin^{-1}\frac{\omega}{\omega_c}$$

where

$$\omega_c^2 = \frac{4}{LC}.$$

The predicted noise figure using MESFET's (with the parameters tabulated in Table I) is plotted in Fig. 6.

The calculated values of L_g, $Z_{\pi d}$, L_d, and f_c are 1.25 nH, 125 Ω, 3.13 nH, and 12.7 GHz, respectively.

Fig. 6 shows a noise-figure variation with frequency, which is characterized by a high value of noise figure at low frequencies and near the cutoff frequencies (corresponding to β values close to unity and π). At other frequencies, the curves show a low noise figure which increases approximately linearly with frequency.

Of particular interest is the observation that the noise figure diminishes with increase of n, at least for the values of n shown in Fig. 6 in accordance with the earlier physical argument.

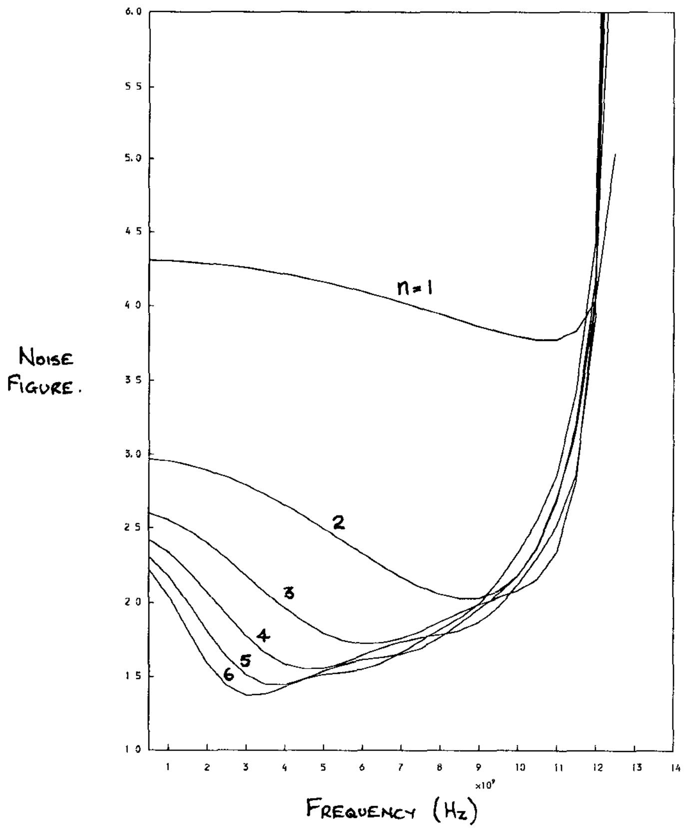

Fig. 6. Distributed amplifier noise figure as a function of frequency with n as a parameter and with component values shown in Table I.

It should be noted that we have assumed a particular value of $Z_{\pi g}$(50 Ω) and that this does not necessarily correspond to a value which minimizes the noise figure. Also, the noise figure depends on the values of R and P, and the values we have used are not necessarily optimum.

V. MINIMUM NOISE FIGURE

It is of interest to consider the minimum theoretical noise figure from the MESFET distributed amplifier. Examination of the noise-figure expression given by (34) shows that, as before, for large n (and for β not close to 0 to π), the second and third terms decrease as n^2 increases and can be made small compared to the unity first term and are therefore negligible. The fourth and fifth terms (representing the noise from the n MESFET's) simplify if we neglect the second and third terms in $f(r,\beta)$ for high n and give

$$f(r,\beta) \approx \sum_{r=1}^{n} (n-r+1)^2. \tag{35}$$

This sums to $n^3/3$ for large n, and the noise figure then becomes

$$F = 1 + \frac{Z_{\pi g} n \omega^2 C_{gs}^2 R}{3g_m} + \frac{4P}{n g_m Z_{\pi g}}. \tag{36}$$

There is an optimum value of the product $nZ_{\pi g}$, which minimizes (36) to give a minimum noise figure $F_{\min}$. These

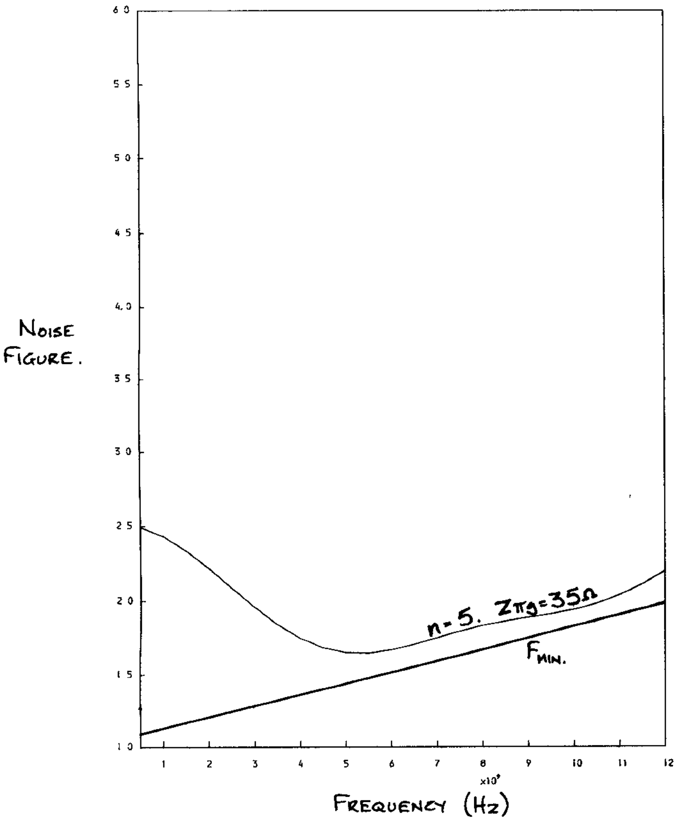

Fig. 7. Distributed amplifier noise figure as a function of frequency for $n = 5$ and $Z_{\pi g} = 35\ \Omega$ together with $F_{\min}$ as a function of frequency.

values are

$$\left.\begin{aligned}(nZ_{\pi g})_{\text{opt}} &= \frac{2}{\omega C_{gs}}\sqrt{\frac{3P}{R}}\\ F_{\min} &= 1+\frac{2\omega C_{gs}}{g_m}\sqrt{\frac{4RP}{3}}\end{aligned}\right\}. \tag{37}$$

Optimization procedures enable convenient combinations of n and $Z_{\pi g}$ to be selected. For example, Fig. 7 shows a noise-figure plot for n equal to 5 and $Z_{\pi g}$ equal to 35 Ω over the frequency range 2–12 GHz, illustrating that this combination of parameters gives an approximately flat characteristic with a slow rise at the band edges. This plot includes all the contributions of (34). Also shown on the same plot is the optimum noise figure of (37).

VI. Comparison of Noise Figure of Distributed Amplifier with that of the Corresponding Resonant Amplifier

It is of interest to compare the minimum noise figure of the distributed amplifier with the minimum noise figure of the resonant MESFET amplifier containing only the same Van der Ziel noise sources.

It can be shown that the minimum noise figure of a resonant amplifier which has an optimized complex source impedance is given by the expression

$$F_{\min} = 1+\frac{2\omega C_{gs}}{g_m}\sqrt{RP\left(1-C_{im}^2\right)}. \tag{38}$$

Thus, we conclude that, at the same frequency with the same device with the same values of RP, the ratio of the excess noise figure for the distributed amplifier (large n) and optimized source resonant amplifier is given by

$$\sqrt{\frac{4}{3\left(1-C_{im}^2\right)}}. \tag{39}$$

If we assume a value of 0.35 for C_{im}, the ratio (39) is 1.23 and the distributed amplifier has an excess noise figure which is 23 percent above that of the corresponding source resonant amplifier.

In practice, this statement requires qualification since a feature of the optimized source resonant amplifier is a significant input mismatch coupled with a reduced bandwidth performance. The input mismatch is often such that a circulator or isolator is required when the resonant amplifier is used in a system, the additional loss of this component adds to the noise figure of the amplifier.

The distributed amplifier, on the other hand, has an inherent matched wide-band gain performance and, having a good input match, does not require additional isolation with consequent noise-figure degradation.

It is then likely that the system noise performance of the distributed amplifier is generally similar to that of the isolated optimized resonant amplifier.

VII. Conclusion

It is concluded that the noise factor of the intrinsic MESFET distributed amplifier, containing only the Van der Ziel generators, has been calculated and is given by (34) of the text. For large n, only the final two terms in this expression are significant and an optimum combination of the parameter $nZ_{\pi g}$ exists such that the minimum noise figure is given by the expression

$$F = 1+\frac{2\omega C_{gs}}{g_m}\sqrt{\frac{4}{3}PR}.$$

Comparison with the corresponding optimized resonant amplifier suggests a similar but narrow-band noise performance, taking into account the mismatch associated with the optimized resonant amplifier and consequent preceding isolator or circulator.

References

[1] W. S. Pervival, British Patent 460 562, July 1936.
[2] E. L. Ginzton, W. R. Hewlett, J. H. Jasberg, and J. D. Noe, "Distributed amplification," *Proc. IRE*, vol. 36, pp. 956–969, Aug. 1948.
[3] E. W. Strid and K. R. Gleason, "A dc-12 GHz monolithic GaAs FET distributed amplifier," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-30, pp. 969–975, July 1982.
[4] K. B. Niclas, W. T. Wilser, T. R. Kritzer, and P. R. Pereira, "On theory and performance of solid state microwave distributed amplifiers," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-31, pp. 447–456, June 1983.
[5] K. B. Niclas and B. A. Tucker, "On noise in distributed amplifiers at microwave frequencies," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-31, pp. 661–668, Aug. 1983.
[6] H. T. Friis, "Noise figure of radio receivers," *Proc. IRE*, pp. 419–422, July 1944.
[7] "Standards on receivers," *Definitions of Terms 1952*, *Proc. IRE*, vol. 40, p. 1681, 1952.

[8] A. Van der Ziel, "Thermal noise in field effect transistors," *Proc. IRE*, vol. 50, pp. 1808–1812, Aug. 1962.
[9] A. Van der Ziel, "Gate noise in field effect transistors at moderately high frequencies," *Proc. IEEE*, vol. 51, pp. 461–467, Mar. 1963.
[10] C. R. Brewitt-Taylor, P. N. Robson, and J. E. Sitch, "Noise figure of MESFETs," *Proc. Inst. Elec. Eng.*, part 1, *Solid State and Electron Devices*, vol. 127 pp. 1–8, Feb. 1980.

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