The Predicted Signal to Noise Performance of a Photodiode-Distributed Amplifier Optical Detector

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ABSTRACT

This paper calculates the signal to noise ratios obtained from an optical detector consisting of a p-i-n photodiode-grounded source MESFET amplifier and also from a p-i-n photodiode-distributed amplifier combination. Expressions are given for both and compared numerically showing that the distributed amplifier combination is superior by up to 10dB for bandwidths up to 40GHz.

INTRODUCTION

In order to minimise the noise power added in an optical communication system photodetector, it is necessary to select the type of following amplifier such that the noise from the amplifier is a minimum with the p-i-n photodetector impedance as the source. A number of amplifier configurations have been used in the past and include the transimpedance amplifier and the grounded source MESFET. As the system bandwidth requirement increased the grounded source becomes less practical. The grounded source configuration suffers from the disadvantage of the need for an equalisation circuit, which enhances the high frequency component of the MESFET drain noise, as well as a correlation noise contribution due to the reactive source impedance. There is also noise originating from the p-i-n photodiode biassing arrangement.

This paper proposes the incorporation of the p-i-n photodiode within the distributed amplifier and calculates the signal to noise ratio at the output of both this arrangement and the unusual grounded source MESFET configuration. The two are then compared numerically.

The calculation assumes that the optical power is the same for the purpose of comparison and that the optical level is such that shot noise can be neglected.

GROUNDED SOURCE MESFET AMPLIFIER

Figure 1 illustrates the equivalent circuit of the grounded source MESFET in which the MESFET is represented by 2 van der Ziel current generators i_g^2 and i_d^2 with a complex correlation coefficient C together with a gate capacitance C_{gs} and output current generator I_d. The gate is fed from a source connected to a photo-diode represented by a shunt capacitor C_d. The p-i-n diode biassing resistor appears as a shunt conductance G_s with associated current generator i_s^2.

The noise generators are given by:

$$\overline{i_g^2} = 4kT_o \frac{\omega^2 C_{gs}^2}{g_m} R df$$

$$\overline{i_d^2} = 4kT_o g_m P df$$

$$\text{and} \quad \overline{i_s^2} = 4kT_o G_s df$$

in which R and P are numerical factors given in Ref.1, k is Boltzmann's constant, T_o is the standard temperature and G_s is the source conductance.

The shunt input combination of C_{ds} and C_{gs} (equal to C_T) and G_s have a low pass characteristic and to preserve the signal spectrum it is necessary to provide an equalisation circuit after the amplification process. One such equalisation circuit is represented in Figure 1 as a series impedance, Z_c, in shunt with the output. For equalisation:

$$Z_c = A(G_s + j\omega C_T)$$

where A is a constant with the dimensions of the square of impedance. It is assumed that this circuit is sufficiently far down the amplification chain for its own noise contribution to be negligible.

Analysis of the circuit enables the signal to noise ratio for the p-i-n diode grounded source amplifier to be calculated in terms of the parameters quoted above as:

$$(\frac{S}{N})_{GS} = \frac{g_m Is^2}{4kT_o[G_s g_m B + \frac{4}{3}\pi^2 C_{gs}^2 RB^3 + (G_s^2 B + \frac{4}{3}\pi^2 C_T^2 B^3)P + \frac{8}{3}\pi^2 C_{gs} C_T C_{im}\sqrt{PRB}]} \quad (1)$$

where the noise power has been integrated over the bandwidth B.

The noise terms in the denominator are due, respectively, to the resistor providing bias for the gate, the gate noise generator, the drain noise generator. The biggest contribution comes from the drain noise generator.

DISTRIBUTED AMPLIFIER

A feature of the distributed amplifier is its low input impedance and flat gain characteristic maintained up to the structure's cut-off frequency' (40GHz or occasionally beyond). Thus, bias to a p-i-n diode photo-detector at the input can be supplied without noise degradation, unlike the grounded source MESFET amplifier: furthermore, no equalisation circuit is necessary and so no consequent enhancement of the drain noise generator's high frequency output will occur.

An earlier paper (Ref.2) has treated the noise behaviour of the distributed amplifier using MESFETs as the active devices when the source impedance is entirely resistive. Appropriate expressions taken from Ref.2 are used in the calculation summarised below.

The resistive nature of the distributed amplifier source impedance can be maintained even with a p-i-n diode photo detector at the input. This desirable feature can be obtained by building the p-i-n diode into a π-section network as shown in Fig.2. The p-i-n capacitance forms one shunt capacitor, a capacitor of identical capacitance is used as the second shunt component and the series inductance is selected so that the low frequency value of $Z\pi g$ is equal to 50Ω, which is the input impedance of the distributed amplifier. The left hand port of this network is terminated in a load equal to $Z\pi g$ and the right hand port is connected to the distributed amplifier. Thus the p-i-n photo detector has been effectively integrated into the distributed amplifier gate line, as illustrated in Fig.2.

Analysis of this configuration yields an expression for the signal to noise ratio for the distributed amplifier given by:

$$(\frac{S}{N})_{DA} = \frac{n^2 g_m^2 Is^2 Z_{\pi g}^2 Z_{\pi d}}{16kT_o\,[\frac{\pi^2}{3} g_m C_{gs}^2 R\overline{\Sigma f(r,\beta)} Z_{\pi d} B^3 + n g_m P Z_{\pi d} B + B + \frac{g_m^2 Z_{\pi g}^2 Z_{\pi d}}{4}\int_0^B (\frac{\sin n\beta}{\sin\beta})^2 df + \frac{n^2 g_m^2 Z_{\pi g} Z_{\pi d} B}{4}]} \quad (2)$$

in which $Z_{\pi g}$ and $Z_{\pi d}$ are the gate and drain line characteristic impedances, n is the number of MESFETs and β is the phase constant at a frequency *f*. The expression

$\Sigma f(r,\beta)$ *is given by* (*Ref.*2)

$$(n-r+1)^2 + \left(\frac{\sin(r-1)\beta}{\sin\beta}\right)^2 + \frac{2(n-r+1)\ \sin(r-1)\beta.\cos}{\sin\beta}$$

The noise terms in the denominator are due, respectively, to the gate noise generators, the drain noise generators, the idle drain load, the idle gate load and the source resistance at the input to the π-network feeding the distributed amplifier.

COMPARISON OF SIGNAL TO NOISE RATIOS FOR DISTRIBUTED AMPLIFIER AND GROUNDED SOURCE AMPLIFIER

We can use expressions (1) and (2) to compare the signal to noise ratios in the two configurations for the same value of I_s, the photodetector output due to the optical signal. Clearly this is a function of the component values in the two circuits and is, therefore, best undertaken numerically.

The Table below gives the values assumed in the comparison. The noise parameters are taken from Ref.3.

Cgs(pF)	g_m(S)	R	P	$\sqrt{RP}\ C_{im}$	n	$Z_{\pi g}(\Omega)$	$Z_{\pi d}(\Omega)$	Gs(S)
0.33	30×10^{-3}	0.3	1.24	0.42	4	50	50	1×10^{-3}

Table 2, below shows the signal to noise ratio for the distributed amplifier configuration normalised to that for the grounded source as a function of bandwidth *B* assuming that the p-i-n diode capacitance, C_d, is equal to C_{gs}.

Bandwidth (GHz)	Ratio (dB)
20	4.8
25	6.7
30	8.3
40	10.6

The effect of the p-i-n diode capacitance, C_d, on the signal to noise ratio for a fixed bandwidth of 40GHz and for a C_{gs} equal to 0.25pF is given in Table 3 below.

Cd (pF)	Ratio (dB)
0.05	4.9
0.10	5.9
0.15	6.8
0.20	7.6
0.25	8.3

We see that, for C_d equal to C_{gs} the distributed amplifier always has a signal to noise ratio benefit compared to the grounded source amplifier over the frequency band 20 to 40GHz at least and that this benefit increases with frequency being 10.6dB at 40GHz. Similarly the effect of incresing C_d, the p-i-n diode capacitance, for fixed C_{gs} at a fixed frequency of 40GHz is that the benefit increases with increasing C_d. An improvement of 8.3dB occurs with C_d equal to 0.25pF.

CONCLUSION

It is concluded that the predicted combination of distributed amplifier and integrated photo-detector gives a superior signal to noise performance to the usual arrangement of photo-detector and grounded source MESFET. The benefit is particularly significant over wide modulation bandwidths such as 40GHz and is a function of the ratio of the capacitance of the p-i-n photo-diode to the gate-source capacitance of the MESFET. Improvements of up to 10dB are predicted.

REFERENCES

1) A Van der Ziel. "Gate Noise in Field Effect Transistors at Moderately High Frequencies". Proc. IEEE, 1964, 51, pp.461-467.

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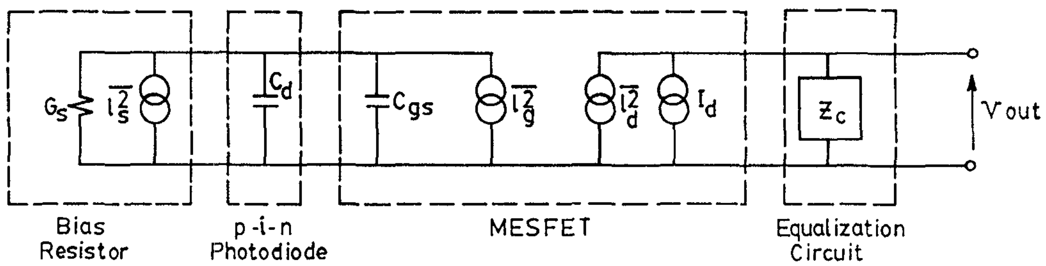

Figure 1: Equivalent circuit of grounded source amplifier with p-i-n photodiode and equalisation circuit.

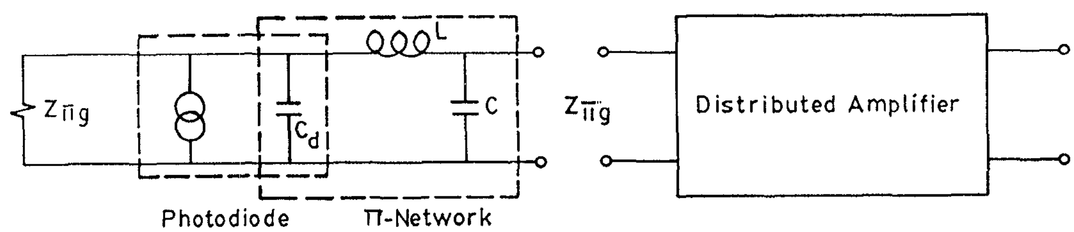

Figure 2: Distributed amplifier with π-section containing p-i-n diode detector.