Signal-To-Noise Performance of the Optical Receiver Using a Distributed Amplifier and P-I-N Photodiode Combination

Jia Yi Liang, *Member, IEEE,* and Colin S. Aitchison, *Fellow, IEEE*

***Abstract*—The signal to noise performance of grounded source amplifier and distributed amplifier optical receiver configurations has been theoretically investigated. This predicts that an improvement of signal to noise ratio up to 12.7 dB is achievable for the distributed amplifier configuration compared with the grounded source in a bandwidth of 40 GHz. Our preliminary experimental results support the theoretical analysis. An optical receiver with 3 dB bandwidth of 20 GHz was fabricated by embedding the p-i-n photodiode into a T-network at the gate line in the distributed amplifier and an average equivalent input noise of 20 pA/Hz$^{1/2}$ was achieved over a bandwidth of 2–18 GHz.**

I. Introduction

As the modulation bandwidth of optical fiber communication system extends to tens of GHz range, the demodulation bandwidth of the photodetecting circuit has to be increased correspondingly without degradation in noise performance. The conventional configuration [1] for large bandwidth receiver systems is the grounded source structure, which is a p-i-n photodiode followed by a MESFET amplifier. This configuration is essentially a low-pass filter structure, as its input impedance is a shunt combination of a bias resistor and the junction capacitance of the photodiode and the gate-source capacitance of the MESFET. In order to minimize the noise contribution from the bias resistor, the value of this resistor is normally large, and the pole of the input circuit is around a few hundred MHz. This produces a correlated noise contribution from the imaginary correlation noise coefficient of the MESFET, as the input impedance is mainly reactive. To obtain a flat frequency response with a grounded source structure, a equalization circuit is required after the amplifier: this has a significant effect on the output noise spectrum and this increases the complexity of the circuit design. As the modulation bandwidth goes higher, the noise increase becomes unusually large, and the detection sensitivity could be degraded to a unacceptable level.

The distributed amplifier gives an alternative approach to a low noise, broad bandwidth photodetection amplifier because of its unique structure [2]–[4]. In a distributed amplifier, the gate and drain capacitance are absorbed by the artificial transmission lines, namely the gate line and drain line. Unlike the grounded source structure, the input impedance of the amplifier is the characteristic impedance of the artificial transmission line which is purely resistive and usually is 50 Ω, therefore no equalization circuit is required after the amplifier. The p-i-n photodiode is placed as the extended first stage of the gate transmission line, and it will not give any reactive contribution to the input impedance since it is resistively terminated. The frequency response of the amplifier is flat up to its cut-off point.

Thus a distributed amplifier receiver has a number of advantages over a grounded source amplifier configuration.

1) The distributed amplifier has already been constructed with flat gain up to 80 GHz [5] and beyond. Because of its low input impedance, no equalization circuit is required afterwards. A grounded source amplifier, however, has to be followed by a equalization circuit to obtain a flat frequency response.
2) The correlated noise contribution from the imaginary correlation coefficient is removed since the source impedance is purely restive. As the input impedance of a grounded source amplifier is mainly capacitive, a correlated noise contribution from the imaginary correlation coefficient of the MESFET is generated.
3) The noise contribution of the configuration has been reduced since the p-i-n diode capacitance is absorbed into the gate line, thus the capacitance of the p-i-n diode will not induce further noise contribution. For a grounded source amplifier, the total noise generation is related to the total input capacitance, which is the sum of the p-i-n diode capacitance and gate capacitance of the MESFET. Therefore, a distributed amplifier configuration will have a superior signal-to-noise performance over the corresponding grounded source amplifier one.

II. Grounded Source Amplifier

The grounded source amplifier is currently used as a photodetection amplifier because of its simple structure and relatively low noise performance up to 10 GHz. It consists of a p-i-n photodiode biased by a large value resistor and a grounded source MESFET as pre-amplifier, followed by a equalization circuit to achieve a flat frequency response. The noise performance of this configuration is mainly decided by the noise behavior of the MESFET and is enhanced by the junction capacitance of the p-i-n diode. The noise behavior of a MESFET is usually represented by the Van de Ziel [6], [7] current noise generators associated with the gate and drain,

Manuscript received January 12, 1995; revised April 10, 1995.
The authors are with the Department of Electrical Engineering and Electronics Brunel University, Uxbridge, Middlsex UB8 3PH, U.K.
IEEE Log Number 9413679.

0018-9480/95$04.00

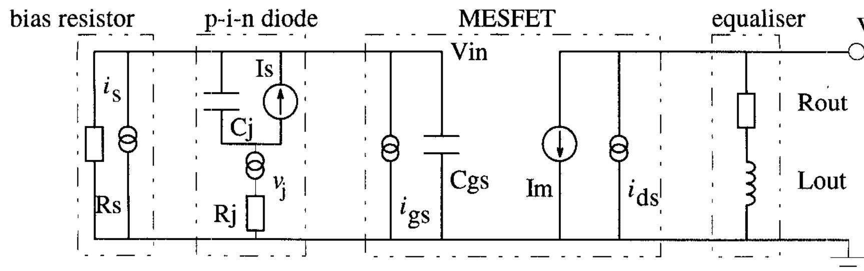

Fig. 1. Equivalent circuit of a grounded source MESFET amplifier and p-i-n photodiode combination.

shown in Fig. 1, whose mean square value $\overline{i_g^2}$ and $\overline{i_d^2}$ are given by the expressions

$$\overline{i_g^2} = \frac{4kT_0\omega^2 C_{gs}^2 R\,df}{g_m} \tag{1}$$

$$\overline{i_d^2} = 4kT_0 g_m P\,df \tag{2}$$

where k is Bolzmann's constant, T_0 is the absolute temperature, ω is the angular frequency, g_m the mutual conductance, and C_{gs} the gate-source capacitance of the MESFET, R and P are the noise coefficients of gate and drain noise generators. These two noise generators represent noise which originates from the same source and must be partially correlated and represented by a complex correlation coefficient C [6], which is defined as

$$C = \frac{\overline{i_d \cdot i_g^*}}{\sqrt{\overline{i_g^2} \cdot \overline{i_d^2}}}, \tag{3}$$

where

$$C = C_r + jC_{im}. \tag{4}$$

The real part of the correlated coefficient C_r is very small for MESFET's and is usually taken as zero [7]. Therefore, with a purely real source admittance, there is no noise power contribution from the cross correlation term. With a complex source admittance, the situation changes and there is an additional noise power contribution from the imaginary component.

Fig. 2 shows a simplified equivalent circuit for a grounded source amplifier and p-i-n diode combination with the MESFET noise source. The p-i-n diode capacitance is C_s so that the total capacitance C_t, is the sum of C_s and C_{gs}. We can see that the input admittance consists of the total input capacitance C_t and a bias conductance G_s, and they form a low pass filter structure whose frequency response roll-offs at a few hundred MHz. In order to maintain a flat frequency response, a equalization circuit is placed after the MESFET amplifier. This can conveniently be represented by an inductor, L_{out}, and resistor, R_{out}, in series as shown in Fig. 2. The input admittance Y_{in} and output impedance Z_{out} are expressed as

$$Y_{in} = G_s + j\omega C_t, \tag{5}$$

$$Z_{out} = R_{out} + j\omega L_{out}. \tag{6}$$

The mean square value of the total noise current at the input is $\overline{i_{gt}^2}$, where

$$\overline{i_{gt}^2} = \left(\overline{i_g} + \frac{Y_{in}}{g_m}\overline{i_d}\right) \cdot \left(\overline{i_g} + \frac{Y_{in}}{g_m}\overline{i_d}\right)^* \tag{7}$$

which can be written as

$$\overline{i_{gt}^2} = \overline{i_g^2} + \frac{Y_{in} \cdot Y_{in}^*}{g_m^2}\overline{i_d^2} + \frac{Y_{in}}{g_m}\overline{i_g \cdot i_d^*} + \frac{Y_{in}^*}{g_m}\overline{i_g^* \cdot i_d}. \tag{8}$$

It is convenient to define ρ by

$$\rho = \frac{Y_{in}^*}{|Y_{in}|}C \tag{9}$$

we can write

$$\overline{i_{gt}^2} = \overline{i_g^2} + \frac{Y_{in} \cdot Y_{in}^*}{g_m^2}\overline{i_d^2} + 2\sqrt{\overline{i_g^2} \cdot \overline{i_d^2}\,\frac{Y_{in} \cdot Y_{in}^*}{g_m^2}}\,\mathrm{Re}\,(\rho) \tag{10}$$

where $\mathrm{Re}\,(\rho)$ is given by

$$\mathrm{Re}\,(\rho) = \frac{\omega C_{im} C_t}{|Y_{in}|}. \tag{11}$$

The noise current contribution from the bias conductance G_s is

$$\overline{i_s^2} = 4kT_0 G_s\,df. \tag{12}$$

The mean square value of the total noise current at the input is expressed as

$$\overline{i_{gt}^2} = 4kT_0 g_m \left[G_s g_m + \frac{R\omega^2 C_{gs}^2}{g_m^2} + \frac{P(G_s^2 + \omega^2 C_t^2)}{g_m^2} + 2C_{im}\sqrt{RP}\,\frac{\omega^2 C_{gs} C_t}{g_m^2}\right] df. \tag{13}$$

The total noise current, $\overline{i_{dt}^2}$, at the output becomes

$$\overline{i_{dt}^2} = \frac{g_m^2 \overline{i_{gt}^2}}{Y_{in} \cdot Y_{in}^*} = \frac{g_m^2 \overline{i_{gt}^2}}{G_s^2 + \omega^2 C_t^2} \tag{14}$$

and the corresponding mean square noise voltage, $\overline{\nu_{out}^2}$ at the output is given by

$$\overline{\nu_{out}^2} = \overline{i_{dt}^2} Z_{out} Z_{out}^* = \overline{i_{dt}^2}(R_{out}^2 + \omega^2 L_{out}^2). \tag{15}$$

Substituting (13) and (14) into (15) gives

$$\overline{\nu_{out}^2} = 4kT_0 g_m \frac{R_{out}^2 + \omega^2 L_{out}^2}{G_s^2 + \omega^2 C_t^2} \left[G_s g_m + \frac{R\omega^2 C_{gs}^2}{g_m^2} + \frac{P(G_s^2 + \omega^2 C_t^2)}{g_m^2} + 2C_{im}\sqrt{RP}\,\frac{\omega^2 C_{gs} C_t}{g_m^2}\right] df. \tag{16}$$

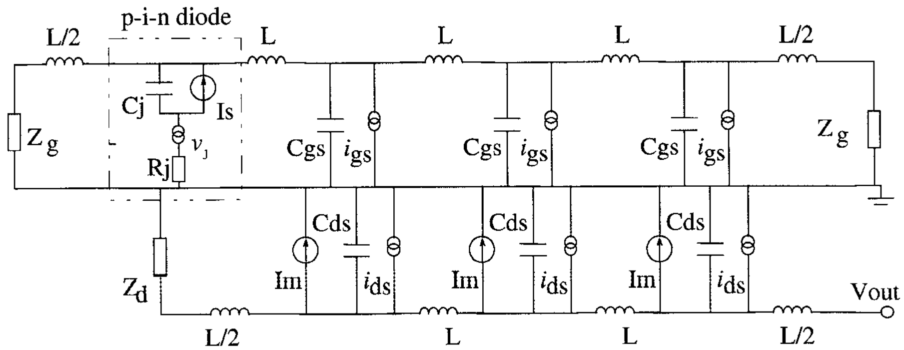

Fig. 2. Equivalent circuit of a distributed amplifier and p-i-n photodiode combination.

In the same way, we can calculate the voltage output, V_{out}, due to a given signal current generator, I_s, from the p-i-n diode. V_{out} is given by

$$V_{out} = \frac{I_s g_m Z_{out}}{Y_{in}} = \frac{I_s(R_{out} + j\omega L_{out}) g_m}{G_s + j\omega C_t}. \quad (17)$$

In order to obtain a flat frequency response at the output load, we define the equalization coefficient, A, which is frequency independent, as

$$A = \frac{R_{out}}{G_s} = \frac{L_{out}}{C_t}. \quad (18)$$

So, (17) and (18) become

$$V_{out} = A g_m \cdot I_s, \quad (19)$$

$$\overline{\nu_{out}^2} = 4kT_0 g_m A^2 \left[G_s g_m + \frac{R\omega^2 C_{gs}^2}{g_m^2} + \frac{P(G_s^2 + \omega^2 C_t^2)}{g_m^2} + 2C_{im}\sqrt{RP}\,\frac{\omega^2 C_{gs} C_t}{g_m^2} \right] df. \quad (20)$$

The noise power, p_n, dissipated in the output load is

$$p_n = \frac{\overline{\nu_{out}^2}}{R_{out}}. \quad (21)$$

Substituting (20) to (21) gives

$$p_n = 4kT_0 g_m \frac{A^2}{R_{out}} \left[G_s g_m + \frac{R\omega^2 C_{gs}^2}{g_m^2} + \frac{P(G_s^2 + \omega^2 C_t^2)}{g_m^2} + 2C_{im}\sqrt{RP}\,\frac{\omega^2 C_{gs} C_t}{g_m^2} \right] df. \quad (22)$$

The total noise output power in a given bandwidth B for a grounded source amplifier and p-i-n diode combination, P_N^{GS}, is obtained by integrating (22) to give

$$P_N^{GS} = \frac{4kT_0 g_m A^2}{R_{out}} \left[G_s g_m B + \frac{4}{3}\pi^2 R B^3 C_{gs}^2 + P\left(G_s^2 B + \frac{4}{3}\pi^2 B^3 C_t^2 \right) + \frac{8}{3}\pi^2 \sqrt{RP} C_{im} B^3 C_t C_{gs} \right]. \quad (23)$$

The signal power, P_S^{GS}, at the output load from the current generator, I_s, due to an incident optical power at the input photodiode is given by

$$P_S^{GS} = \frac{g_m^2 A^2 I_S^2}{R_{out}}. \quad (24)$$

From the equation for total noise power, we can see that the first term is the noise contribution from the photodiode bias resistor, and if the value of the resistor is chosen to be large enough, the noise contribution can be negligible; the second term is the noise power generated from the gate noise source, which is related to gate capacitance C_{gs} and proportional to B^3; the third term is from the drain noise source, and it is proportional to C_t^2 and B^3, plus a contribution from the bias conductance. The final term is the noise contribution from the imaginary correlation coefficient from the MESFET due to the complex input admittance, this contribution is proportional to the total capacitance of the input capacitance and B^3. It is clear that increasing the junction capacitance of the photodiode will increase the total output noise power. Moreover, the principle noise contributions are all proportional to bandwidth cubed, which means that the total noise power will increase rapidly with the increase of bandwidth, and this makes low noise, broad bandwidth operation of this structure even more disadvantageous.

III. Distributed Amplifier

The distributed amplifier was first proposed by Percival [8] in 1936 in order to create a broad bandwidth amplifier without the usual gain-bandwidth constraint implicit in a resonant amplifier using active devices. Current distributed amplifiers use MESFET's as the active devices. The configuration of a distributed amplifier is very different from the ordinary resonant amplifier; it is constructed by two artificial transmission lines of which one absorbs the gate-source capacitors of the MESFET's and the other the drain-source capacitors. The p-i-n diode is place as the first section in the gate line which is shown in Fig. 3. As the gain and noise performance of a distributed amplifier has been already investigated by Aitchison [9], we can calculate the results for the distributed amplifier and p-i-n diode combination. For convenience, we use the simplified MESFET model and assume that the artificial transmission lines for the gate and drain line are loss-free. The characteristic impedance of the

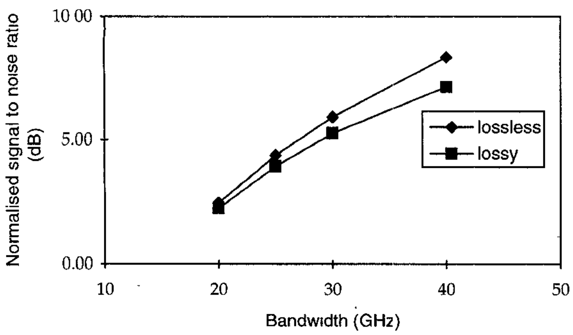

Fig. 3. The signal to noise ratio for the distributed amplifier combination normalized to that for grounded source for both lossless and lossy photodiode as a function of bandwidth.

gate and drain line are $Z_{\pi g}$ and $Z_{\pi d}$, respectively. The gate line is terminated with impedance $Z_{\pi g}$ at both ends, while the drain line is terminated at its left-hand side with impedance $Z_{\pi d}$. In order to achieve the maximum frequency independent available forward gain, the imaginary part of the propagation constants in the gate and drain line have to be identical. This requires the inductance, L_g, in the gate line to be equal to the inductance, L_d, in the drain line, and C_{gs} to be equal to C_{ds}, if the two characteristic impedances are identical.

To calculate the noise contributions in a distributed amplifier-p-i-n diode combination, we assume that the noise contribution from the p-i-n diode is negligibly small and only take the noise sources from the distributed amplifier in to account. The total noise power dissipated in the output load can be calculated from the various noise source following the calculation of [9].

A. Noise Contribution from Gate Termination Impedances ($Z_{\pi g}$)

The noise power available from the left-hand termination impedance at the standard temperature, T_0, is $kT_0\,df$, therefore the noise power dissipated in the output load is $G_f kT\,df$, in which G_f is the forward available gain. The noise power, p_1' is expressed as

$$p_1' = kT_0\,\frac{n^2 g_m^2 Z_{\pi g} Z_{\pi d}}{4}\,df. \tag{25}$$

The noise power dissipated in the output load, due to the right-hand side terminating impedance, is $G_r kT_0\,df$, in which G_r is the reverse gain The noise power, p_2', is expressed as

$$p_2' = kT_0\,\frac{g_m^2 Z_{\pi g} Z_{\pi d}}{4}\left(\frac{\sin n\beta}{\sin\beta}\right)^2 df. \tag{26}$$

B. The Noise Contribution from the Drain Termination Impedance

The noise power contribution from the drain termination impedance, p_3', in the drain line is

$$p_3' = kT_0\,df \tag{27}$$

C. The Noise Power Contribution Associated with the MESFET's

The noise behavior of the MESFET can be represented by gate and drain noise current generators with associated complex correlation coefficient. In practice, this correlation coefficient is substantially imaginary, Consequently since the characteristic impedances of the gate and drain lines are both real, there will be no cross correlation noise term contribution to the power in the load [9]. The total noise power, p_4', due to the n MESFET noise current generators in the drain line is given by

$$p_4' = kT_0 n g_m P Z_{\pi d}\,df. \tag{28}$$

The noise contribution from the gate noise sources is more complicated as each of the individual noise current sources delivers noise to the load through several routes and these noise currents are completely correlated. This noise contribution, p_5', is expressed as

$$p_5' = 4kT_0\left(\frac{1}{4}\,g_m Z_{\pi g}\right)^2 Z_{\pi d}\,\frac{\omega^2 C_{gs}^2}{g_m}\,R \cdot \sum_{r=1}^{n} f(r,\beta)\,df \tag{29}$$

where

$$f(r,\beta) = (n-r+1)^2 + \left[\frac{\sin(r-1)\beta}{\sin\beta}\right]^2 + \frac{2(n-r+1)\sin(r-1)\beta\cos r\beta}{\sin\beta} \tag{30}$$

when n is large enough, we have approximately

$$f(r,\beta) = (n-r+1)^2. \tag{31}$$

The total noise output dissipated in the load, p_t', is the sum of all the noise contributions

$$p_t' = p_1' + p_2' + p_3' + p_4' + p_5'. \tag{32}$$

The total noise power, P_N^{DA} dissipated at the output in a bandwidth B is obtained by integrating (32)

$$P_N^{DA} = kT\left[\frac{\pi^2}{3}\,g_m C_{gs}^2 R\overline{\Sigma f(r,\beta)} Z_{\pi d} Z_{\pi g}^2 B^3 + n g_m P Z_{\pi d} B + B + \frac{g_m^2 Z_{\pi g}^2 Z_{\pi d}}{4}\int_0^B\left(\frac{\sin n\beta}{\sin\beta}\right)^2 df + \frac{n^2 g_m^2 Z_{\pi g}^2 Z_{\pi d} B}{4}\right]. \tag{33}$$

The signal power dissipated at the output from the input current, I_s, generated in the p-i-n diode by a given input optical power is expressed as

$$P_S^{DA} = \frac{I_S^2 n^2 g_m^2 Z_{\pi g}^2 Z_{\pi d}}{16}. \tag{34}$$

TABLE I
CIRCUIT VALUES USED IN SIGNAL TO NOISE RATIO COMPARISON

Cgs(pF)	gm(S)	R	P	$(RP)^{1/2}$ Cim	n	Zπg(Ω)	Zπd(Ω)	Gs(S)
0.25	0.03	0.3	1.24	0.42	4	50	50	10^{-3}

By comparing (33) and (23), we can see the noise advantages of the distributed amplifier configuration:

1) Some of the noise terms are proportional to bandwidth instead of bandwidth cubed.
2) The noise output is not a function of the p-i-n diode capacitance.
3) There is no cross correlation noise contribution to the distributed amplifier.

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

It is useful to compare the output signal to noise ratios on the two systems on the assumption that both configurations are build using the same MESFET and the optical input power is the same in both cases.

The signal-to-noise ratio is defined as the signal power divided by the noise power dissipated in the output load. From (23) and (24), the signal to noise ratio of a grounded source amplifier p-i-n diode combination is

$$\frac{P_S^{GS}}{P_N^{GS}} = \left[\frac{I_s^2 g_m}{4kT_0} \Big/ G_s g_m B + \frac{4}{3}\pi^2 R B^3 C_{gs}^2 + P\left(G_s^2 B + \frac{4}{3}\pi^2 B^3 C_t^2\right) + \frac{8}{3}\pi^2 \sqrt{RP} C_{im} B^3 C_T C_{gs}\right]. \quad (35)$$

From (33) and (34), the signal to noise ratio of a distributed amplifier-p-i-n diode combination is

$$\frac{P_S^{DA}}{P_N^{DA}} = \left(\frac{n^2 g_m^2 I_S^2 Z_{\pi g}^2 Z_{\pi d}}{16kT_0} \Big/ \frac{\pi^2}{3} g_m C_{gs}^2 R \overline{\Sigma f(r,\beta)} \cdot Z_{\pi d} Z_{\pi g}^2 B^3 + n g_m P Z_{\pi d} B + B + \frac{g_m^2 Z_{\pi g}^2 Z_{\pi d}}{4}\left\{\int_0^B \left(\frac{\sin n\beta}{\sin\beta}\right)^2 df + n^2\beta\right\}.\right) \quad (36)$$

In order to compare the performance of the two different photo-detection amplifier configurations, we have to use the ratio of the signal to noise ratios, assuming that we use the same p-i-n diode and MESFET's and that the optical input power is the same. Clearly, this is a function of the component values in the two circuits and is, therefore, best undertaken numerically.

Table I gives the parametric values of the components in the comparison. The noise parameters are taken from the literature.

Using the assumed MESFET and circuit parameters given in Table I, the signal to noise ratio for the distributed amplifier configuration normalized to that for the grounded source as a function of bandwidth B and assuming that the p-i-n photodiode capacitance C_j, is equal to C_{gs} has been calculated and is given in Table II.

TABLE II
SIGNAL TO NOISE RATIO FOR DISTRIBUTED AMPLIFIER NORMALIZED TO THAT OF THE GROUNDED SOURCE AMPLIFIER

Bandwidth (GHz)	Ratio (dB)
20	2.48
25	4.38
30	5.90
40	8.34

TABLE III
THE IMPROVEMENT IN SIGNAL TO NOISE RATIO AS A FUNCTION OF THE p-i-n DIODE CAPACITANCE AT A BANDWIDTH OF 40 GHz

C_j (pF)	Ratio (dB)
0.05	4.85
0.10	5.85
0.15	6.76
0.20	7.58
0.25	8.34

For a given MESFET gate-source capacitance with assumed value of 0.25 pF, the effect of the p-i-n diode capacitance, C_j, on the normalized signal to noise ratio for a fixed bandwidth of 40 GHz is given in Table III.

We can see that, for C_j 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 from 20–40 GHz at least, and that this benefit increases with the bandwidth and the improvement is 8.34 dB in a bandwidth of 40 GHz for C_{gs} equal to 0.25 pF. Similarly, the effect of increasing the p-i-n diode capacitance, C_j, for a fixed gate-source capacitance, C_{gs}, of the MESFET in a bandwidth of 40 GHz is that the benefit of the signal to noise ratio increases with increasing C_j.

V. THE EFFECT OF LOSS IN THE p-i-n PHOTODIODE

In the previous section, we considered the noise performance with the intrinsic models both for the MESFET and p-i-n diode. However in practice, there is always junction loss in a photodiode which gives an extra noise contribution. This extra noise generation could contributed up 22% of the total noise output power for the distributed amplifier arrangement [10]. The value of the photodiode junction resistance R_j is about 10 Ω, and its noise contribution must be taken into account. This can be expressed as a noise voltage source $\sqrt{\overline{\nu_j^2}}$, where

$$\overline{\nu_j^2} = 4kT_0R_j\, df. \tag{37}$$

The integrated noise contribution at the output of the grounded source amplifier due to the diode resistance is, if C_j is assumed equal to C_{gs}

$$P_{N,pin}^{GS} = \frac{16\pi^2 kT_0 R_j g_m^2 B^3 C_j^2 A^2}{3R_{out}}. \tag{38}$$

The case of the distributed amplifier is more complicated. The integrated noise contribution of the diode junction resistor at the output of the distributed amplifier becomes

$$P_{N,pin}^{DA} = 0.43kT_0\pi^2 B^3 C_{gs}^2 R_j n^2 g_m^2 Z_{\pi g}^2 Z_{\pi d}. \tag{39}$$

The sensitivity of the two amplifier p-i-n diode combinations can be expressed in term of signal-to-noise ratio for a given optical power into the photodiode and can be compared by the signal-to-noise ratios of the two combinations with the same optical input power into the photodiodes.

Using (23), (24), and (38), the signal to noise ratio of the grounded-source amplifier with the additional loss from the p-i-n photodiode, R_j, becomes

$$\begin{aligned}\left(\frac{S}{N}\right)_{GS} = &\left[\frac{I_S^2 g_m}{4kT_0}\Big/ G_S g_m B + \frac{4}{3}\pi^2 B^3 C_{gs}^2 R\right.\\ &+ P\left(G_s^2 B + \frac{4}{3}\pi^2 B^3 C_t^2\right) + \frac{8}{3}\pi^2\sqrt{RP}\\ &\left.\cdot C_{im} B^3 C_t C_{gs} + \frac{\pi^2 R_j g_m B^3 C_j^2}{3}\right].\end{aligned} \tag{40}$$

While using (33), (34), and (39), the signal-to-noise ratio of the distributed amplifier with the additional loss from the p-i-n photodiode, R_j, is

$$\begin{aligned}\left(\frac{S}{N}\right)_{DA} = &\left[\frac{I_S^2 n^2 g_m^2 Z_{\pi g}^2 Z_{\pi d}}{16kT_0}\Big/ \frac{\pi^2}{3} g_m C_{gs}^2 R\overline{\Sigma f(r,\beta)}\right.\\ &\cdot Z_{\pi d} Z_{\pi g}^2 B^3 + n g_m P Z_{\pi d} B\\ &+ B + \eta + \frac{n^2 g_m^2 Z_{\pi g} Z_{\pi d} B}{4}\\ &\left.+ 0.43\pi^2 B^3 R_j n^2 g_m^2 Z_{\pi g}^2 Z_{\pi d} C_{gs}^2\right],\end{aligned} \tag{41}$$

where

$$\eta = \frac{g_m^2 Z_{\pi g}^2 Z_{\pi d}}{4}\int_0^B \left(\frac{\sin n\beta}{\sin\beta}\right)^2 df. \tag{42}$$

Using the same parameters as before (see in Table I), (41) yields a new signal to noise improvement in favor of the distributed amplifier configuration and is shown in Table IV for the value of R_j equal to 10 Ω and C_j equal to C_{gs}.

A comparison of Table II with Table III shows that the effect of the photodiode junction resistance is to reduce the signal to noise benefit of the distributed amplifier configuration by between 0.2 dB for a bandwidth of 20 GHz and 1.2 dB for 40 GHz. The comparison is shown in Fig. 3.

TABLE IV
THE S/N RATIO FOR DISTRIBUTED AMPLIFIER NORMALIZED TO THE GROUNDED SOURCE ONE FOR R_j = 10 Ω

Bandwidth (GHz)	Ratio (dB)
20	2.26
25	3.95
30	5.25
40	7.13

VI. THE EFFECT OF THE FREQUENCY DEPENDENT CHARACTERISTIC IMPEDANCE OF DISTRIBUTED AMPLIFIER

The previous discussion is based on the assumption that the characteristic impedances are frequency independent for the distributed amplifier. However, the characteristic impedance of the artificial transmission lines which form the gate and drain lines for a distributed amplifier are frequency-dependent. This affects the gain and noise performance of a distributed amplifier especially at frequencies near cut-off frequency.

The impedances of the artificial transmission lines in a distributed amplifier are frequency dependent and are given by

$$Z_\pi = \frac{Z_0}{\sqrt{1-\left(\frac{f}{f_C}\right)^2}} \tag{43}$$

where

$$Z_0 = \sqrt{\frac{L}{C}} \tag{44}$$

and Z_π is the frequency-dependent characteristic impedance, L the inductance and C the capacitance, f the frequency and f_C the cut-off frequency of the line which is defined as

$$f_c = \frac{1}{\pi\sqrt{LC}}. \tag{45}$$

Fig. 4 shows a distributed amplifier with frequency dependent line terminations. The integrated noise power at the output of the distributed amplifier in a bandwidth $\alpha f_C (\alpha < 1)$ can then be expressed as

$$\begin{aligned}P_N^{DA} = kT_0 &\left[\frac{\pi^2}{3} g_m R C_{gs}^2 Z_0^3 \overline{\Sigma f(r,\beta)}\right.\\ &\cdot (tg\,\sin^{-1}\alpha - \sin^{-1}\alpha + n g_m P Z_0 f_C \sin^{-1}\alpha\\ &\left.+\alpha f_C + \chi + \frac{Z_0^2 n^2 g_m^2 f_C}{8}\ln\frac{1+\alpha}{1-\alpha}\right]\end{aligned} \tag{46}$$

where

$$\chi = \frac{g_m^2 Z_{\pi g}^2 Z_{\pi d}}{4}\int_0^{\alpha f_0}\left(\frac{\sin n\beta}{\sin\beta}\right)^2 df \tag{47}$$

and where we have assumed that both the drain and gate lines have the same cut-off frequency. The signal power of the distributed amplifier at the output due to a current generator at the input is given by

$$P_S^{DA} = \frac{I_S^2 n^2 g_m^2 Z_0^3}{16(\sqrt{1-\alpha^2})^3}. \tag{48}$$

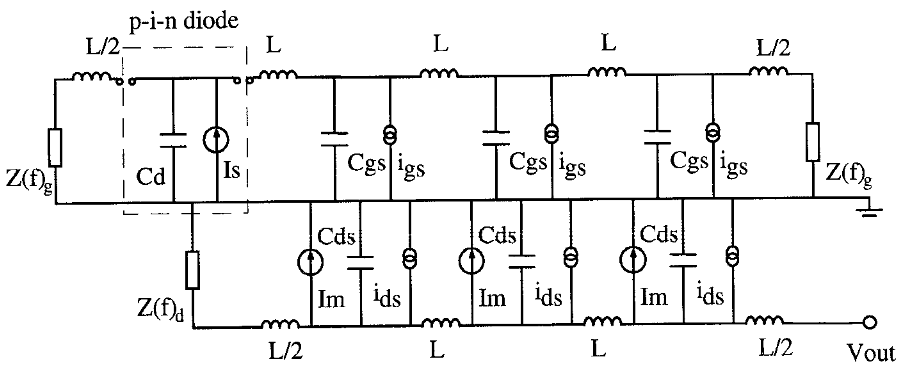

Fig. 4. Equivalent circuit of a distributed amplifier with frequency dependent terminations and p-i-n photodiode combination.

TABLE V
S/N Ratio of Distributed Amplifier with the Frequency-Dependent Loads Normalized to the Grounded Source Amplifier

Bandwidth (GHz)	Ratio (dB)
20	7.06
25	8.94
30	10.5
40	12.7

TABLE VI
The Improvement in the Normalized Signal to Noise Ratio as a Function of the p-i-n Diode Capacitance at a Bandwidth of 40 GHz

C_J (pF)	Ratio (dB)
0.05	9.31
0.10	10.3
0.15	11.2
0.20	12.0
0.25	12.7

The signal to noise ratio of for the distributed amplifier configuration with the correct frequency dependent terminations become

$$\frac{P_S^{DA}}{P_N^{DA}} = \left[\frac{I_S^2 n^2 g_m^2 Z_0^3}{16kT_0(\sqrt{1-\alpha^2})^3} \bigg/ \frac{\pi^2}{3}\, g_m R C_{gs}^2 Z_0^3 \Sigma \overline{f(r,\, \beta)} \cdot (tg \sin^{-1}\alpha - \sin^{-1}\alpha + n g_m P Z_0 f_C \sin^{-1}\alpha + \alpha f_C + \chi + \frac{Z_0^2 n^2 g_m^2 f_C}{8} \ln\frac{1+\alpha}{1-\alpha}\right]. \quad (49)$$

Using the assumed values of MESFET as before, the calculated signal to noise ratios for the distributed amplifier with the correct frequency dependent terminations normalized to that for the grounded source amplifier are shown in Table V as a function of bandwidth B assuming that the p-i-n diode capacitance C_j, is 0.25 pF and is equal to C_{gs}.

Table VI shows the normalized signal to noise ratio for a fixed bandwidth of 40 GHz at a fixed gate-source capacitance of 0.25 pF, with C_j as a parameter.

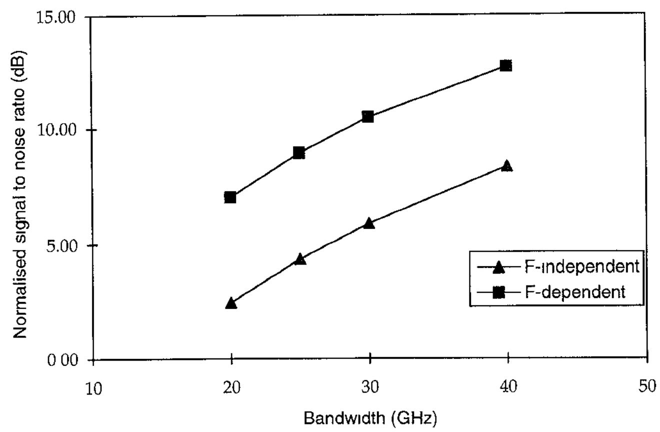

Fig. 5. The normalized S/N ratio of a distributed amplifier over a grounded source one for both frequency-dependent and -independent terminations as a function of bandwidth.

Comparison of Table V with Table II shows that the effect of the frequency dependent characteristic impedance of the distributed amplifier with the correct terminations increases the signal to noise behavior of the distributed amplifier by 4.6 dB for a bandwidth of 20 GHz and 4.4 dB for 40 GHz, (the bandwidth is selected to be 80% of the cut-off frequency for the distributed amplifier arrangement). Fig. 5 shows the signal to noise ratio improvement for this arrangement for the bandwidth between 20–40 GHz.

Similarly, the comparison of Table VI and Table III shows the benefit in signal to noise ratio as a function of the p-i-n diode junction capacitance, C_j. The improvements are about 4.5 dB for C_j values between 0.05–0.25 pF. Fig. 6 gives the normalized signal to noise improvement as a function of C_j over this range.

We see that using the correct frequency dependent terminations increases the signal to noise performance for a distributed amplifier configuration, because this increases the signal power more than the integrated noise power at the output.

VII. Preliminary Experimental Results

A photodetection circuit consisting of a p-i-n diode and a distributed amplifier has been fabricated on a Alumina substrate. This uses a BT&D p-i-n photodiode and an Avantek MGA61000 amplifier. The MGA61000 monolithic distributed

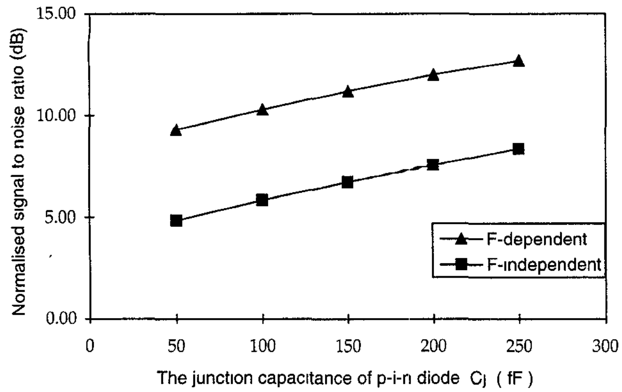

Fig. 6. The S/N ratio of a distributed amplifier and p-i-n diode combination normalized to a grounded source configuration for both frequency-dependent and -independent terminations as a function of the p-i-n diode capacitance.

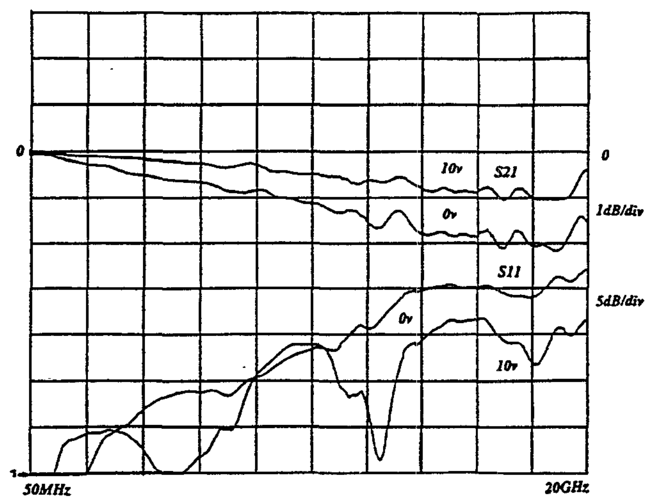

Fig. 7. The measured insertion and return losses of the T-network with an embedded p-i-n photodiode.

amplifier has a flat gain performance up to 18 GHz. The p-i-n diode from BT&D has a junction capacitance of 0.15 pF and an optical responsivity of 1.0 A/W at a wavelength of 1.0–1.6 μm. The p-i-n diode is substrate-illuminated and the optical input beam has to be perpendicular to the photo sensitive area of the p-i-n diode. A small angular misalignment will lead to roll-off at high frequencies due to the internal diffusion capacitance of the diode.

The p-i-n diode has been successfully embedded into a 50 Ω T-network using unencapsulated components together with a biasing arrangement. This T-network is used as an extended first section of the gate line of the distributed amplifier. The microwave performance of this network has been evaluated at bias of 0 and -10 V. The results are shown in Fig. 7. The measured insertion loss of this arrangement is 0 dB at 50 MHz and increases to 1 dB at 20 GHz at -10 V bias. The return loss is better than -18 dB over the same frequency range. Both results are considered to be satisfactory.

The monolithic distributed amplifier has been successfully mounted on an Alumina substrate with the T-section as the first stage of the gate line, in which the unencapsulated p-i-n photodiode was incorporated. The microwave measurement shows a gain of around 6 dB with a 3-dB bandwidth of 20

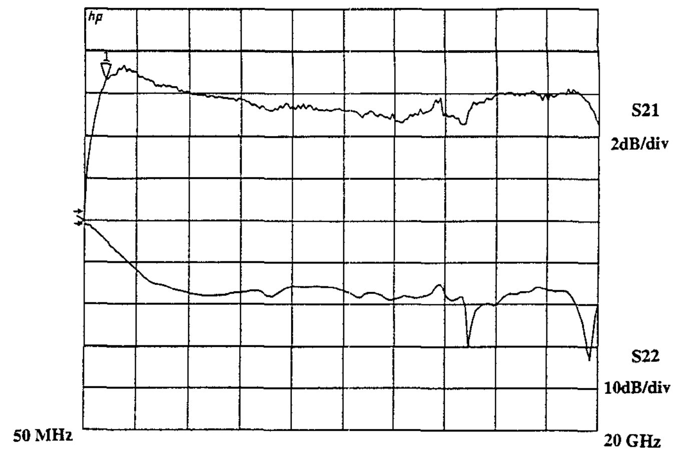

Fig. 8. The measured gain (S21) and return loss (S22) of a distributed amplifier and p-i-n photodiode combination.

GHz together with the return loss S22 better than -15 dB over the bandwidth of 2.5–20 GHz as illustrated in Fig. 8.

Examination of the noise performance of this optical receiver is undertaken by measuring the noise output the distributed amplifier and p-i-n photodiode combination by a calibrated spectrum analyzer. A broadband microwave amplifier with a total gain of over 50 dB was used to amplify the noise output power to a sufficient level to overcome the noise floor of the spectrum analyzer. The measured noise output power was then converted into the input equivalent noise current as the gain of the post amplifier and the transimpedance of the optical receiver are both known. The preliminary experimental results showed the input equivalent noise current is around 20 pA/(Hz)$^{1/2}$ in the bandwidth 2–18 GHz. Fig. 9 shows that the noise level is flat with frequency, unlike the grounded source configuration.

These figures can be used to calculate the optical power required to produce a signal-to-noise ratio of 6 (8 dB) at the output. This figure, which corresponds to an error rate of 1 in 10^{-9}, is known as the optical detection sensitivity. For the purpose of comparing this with published results we select a bandwidth of 10 GHz, though the structure bandwidth is greater. The calculated optical sensitivity based on the measured data given above is -21 dBm. This compares favorably with the grounded source arrangement described in [12] and [14]. For the corresponding conditions, the optical sensitivity is predicted to be -20 dBm [14] for one device (HBT) and -20.4 dBm [12] for another (HEMT) in the same bandwidth. Our result is regarded as encouraging, since neither the p-i-n diode nor the amplifier are selected for optimum noise parameters, nor is the circuit optimized.

VIII. Conclusion

The signal to noise performances for the grounded source amplifier p-i-n photodiode and the distributed amplifier p-i-n diode combinations have been theoretically investigated. This shows that the distributed amplifier configuration has superior signal to noise performance to that of grounded source. The initial results shows that an improvement on signal to noise ratio up to 8.4 dB is predicted for a bandwidth

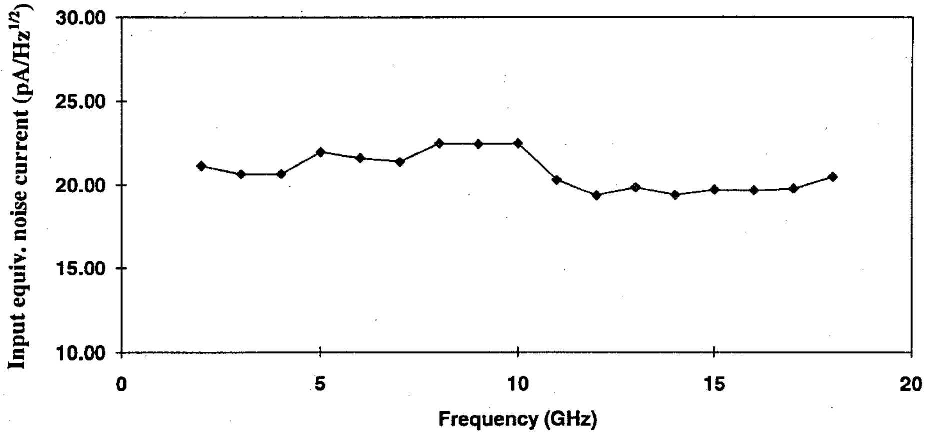

Fig. 9. The measured equivalent input noise current of the distributed amplifier photodetector.

of 40 GHz with assumed circuit parameters, assuming that the characteristic impedances of the distributed amplifier are frequency-independent. By taking the junction resistance of the p-i-n photodiode into account, the extra noise from the p-i-n diode reduces the advantage by up to 1.2 dB at 40 GHz bandwidth. However, the frequency dependent effect of the characteristic impedances of a distributed amplifier suggests that the signal to noise benefit can be improved to 12.7 dB.

The preliminary experimental investigation was based on a distributed amplifier. The photo-detector distributed amplifier was fabricated by embedding the p-i-n photodiode into a T-section of the gate line of the distributed amplifier. This circuit provides about 6 dB gain at a bandwidth of 20 GHz and the measured average input noise current over the bandwidth of 2–18 GHz is about 20 pA/Hz$^{1/2}$. This corresponds to optical sensitivity of −21 dBm for a 10-GHz bandwidth system.

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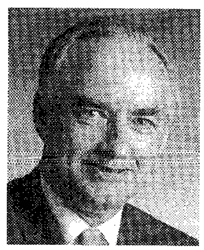
Jia Yi Liang (M'92) was born in Heilongjiang Province, China, on Jan. 2, 1964. He received the B.Sc. degree from the Department of Engineering Optics, Beijing Institute of Technology, China in 1984, and finished his Ph.D. at the Department of Electrical and Electronic Engineering, University College, London University, UK in 1991.

He joined the Department of Electrical Engineering and Electronics, Brunel University, UK, as a Research Fellow in August 1991. He has then worked on high-speed, broadband optoelectronic devices, and microwave devices.



Colin S. Aitchison (A'87–SM-90–F'94) received the B.Sc. from Imperial College in London in 1955.

He joined Philips Research Laboratories where he ran a research group concerned with novel microwave active components including parametric amplifiers and other solid state circuits. In 1972, he joined Chelsea College, University of London, and became Professor and Head of Department, extending his research interests to include distributed amplifiers. In 1984, he joined ERA Technology to establish an active microwave research group concerned with distributed amplifiers, samples, and microwave power amplifiers. In 1989, he joined Brunel University continuing with his active research activities. He is currently Professor and Head of Department. He has published 120 papers.

He is a member of the IEE.