Transimpedance Amplifier for a 2.5 Gbit/s Direct Transmission Optical System using GaAs MESFETS

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ABSTRACT

This paper shows a new closed form expressions intended to analyze the cascode structure with resistive feedback used as Transimpedance Amplifier, derived from the equivalent circuit parameters of the FETS. The predicted transimpedance magnitude, -3 dB bandwidth and ripple are in good agreement with simulations. We used this technique to implement a DC to 2.5 GHz amplifier on GaAs MMIC, with 67 dBΩ of transimpedance and a good noise performance. Using a commercially available photodiode and the described amplifier it has been constructed an optical receiver with a flat responsivity of 32 dB-A/W and 6 pA/$\sqrt{}$(Hz) of equivalent input noise current averaged in band.

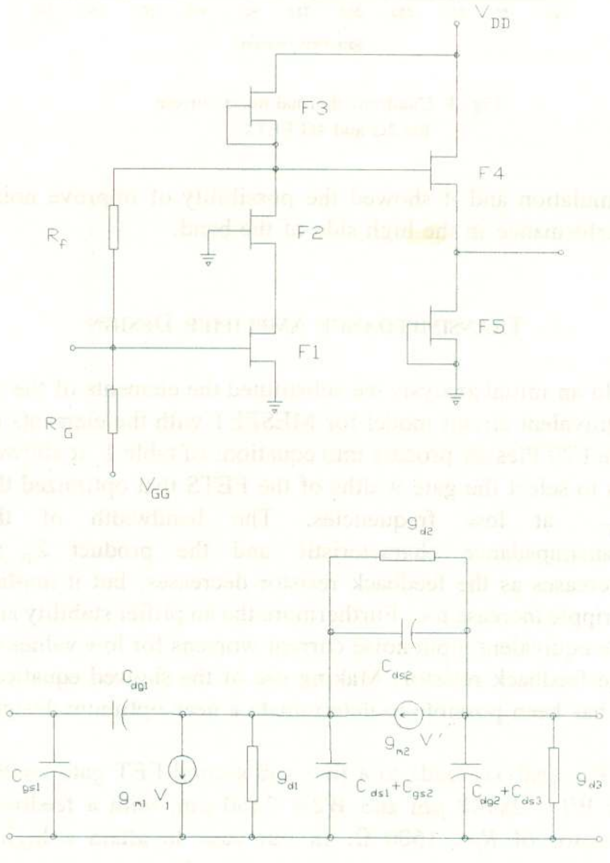

Fig. 1 (a) Cascode structure with active load and resistive feedback
(b) Equivalent Circuit without feedback

INTRODUCTION

The high bit rates used in direct transmission optical systems, on the order of few Gbit/s, lead to Transimpedance Amplifiers (TIA) that can be implemented with MMIC technology. The cascode with resistive feedback (fig. 1a) is the most popular structure [1-8] because of its high gain, but its bandwidth is limited by an increase of the ripple and of the amplifier instability as well as noise current at the input for low feedback resistances. In this communication we show a new set of closed form equations derived from the equivalent circuit elements of the FET model, which allows us to compute with precision the response magnitude, ripple and bandwidth. With the noise parameters of the model given by the manufacturer and a simple expression for the equivalent input noise current we have performed the analysis of the FET gate width and the drain current allowing us the best selection of FET dimensions. Using these expressions we have designed and implemented an MMIC amplifier in GaAs technology with a cascode structure followed by two more stages for gain and output matching. The TIA was fabricated on F20 Plessey process with 0.5 μm gate length and it was used to implement an optical receiver with a commercially available photodiode.

ANALYSIS OF THE CASCODE WITH FEEDBACK

Transimpedance Characteristic Analysis

The admittance parameters of a TIA with this structure can be derived using the equivalent circuit of the cascode structure with an active load (Fig. 1b). Using these parameters, the transimpedance characteristic for a cascode with resistive feedback can be expressed as:

$$Z_T = -\frac{|Z_{T0}|}{1-f^2/f_0 f_2 + jf/f_0[1-(f/f_1)^2]} \qquad (1)$$

where we have used the definitions of Table 1. The equations for the frequency of the maximum f_m, the ripple r, and the -3 dB bandwidth f_c can be obtained from an approximated form of (1), and are shown in Table 1. The transimpedance calculated with (1) for a cascode with buffer followed by a common source stage and a second buffer,

TABLE I

$$g_f = 1/R_f \qquad \alpha = \frac{g_{d1}}{(g_{d2}+g_{m2})}$$

$$\tau_{01} = \frac{C_{ds1}+C_{dg1}+C_{gs2}+C_{ds2}}{g_{d1}+g_{d2}+g_{m2}}$$

$$\tau_{03} = \frac{C_{dg2}+C_{ds3}}{g_{d3}+g_f}\,\frac{1+\alpha[1+C_{ds2}/(C_{dg2}+C_{ds3})]}{1+\alpha[1+g_{d2}/(g_{d3}+g_f)]}$$

$$A_{V0} = -\frac{g_{m1}-(1+\alpha)g_f}{\alpha g_{d2}+(1+\alpha)(g_{d3}+g_f)} \qquad f_1 = \frac{1}{2\pi\sqrt{\tau_{01}\tau_{03}}}$$

$$f_2 = \frac{1}{2\pi(\tau_{01}+\tau_{03})} \qquad Z_{T0} = -\frac{R_f}{1-1/A_{V0}}$$

$$\beta = \frac{g_{m1}}{(g_{d1}+g_{d2}+g_{m2})} \qquad f_0 = \frac{1}{2\pi}\,\frac{|A_{V0}|}{R_f\,[C_{gs1}+(1+\beta)C_{dg1}]}$$

$$f_m = \sqrt{f_0 f_2(1-f_2/2p^2 f_0)} \qquad r^2 = \frac{1}{(f_2/p^2 f_0)(1-f_2/4p^2 f_0)}$$

$$f_c^2 = f_m^2\left(1+\sqrt{1+f_2^2 f_0^2/f_m^4}\right) \qquad p(f_m) = \frac{1}{1-(f_m/f_1)^2}$$

shows in fig. 2 a close agreement with the simulated characteristic.

Noise Analysis

For an optical receiver made up of photodiode, matching network and TIA, the equivalent input noise current appearing across the photodiode junction capacitance is showed in [9,10] and may be applied to the particular case of a TIA with open input. It can be written as:

$$\langle i_n^2 \rangle = 4kTR_n|Y_o|^2 \tag{2}$$

where R_n is the noise resistance and Y_o the source admittance for optimum noise figure of the TIA. Using (2) and the FETS noise parameters of the Plessey F20 process we have plotted in fig. 3 the squared equivalent input noise current at 1.5 GHz as a function of the gate width of the first FET for 2 and 4 gates FETS. This figure shows that a minimum is attained if the first FET of the structure has two gates of 100 μm width and a drain current of $0.5I_{DSS}$.

In a similar way it can be obtained the equivalent input noise current for a photodiode directly connected to the TIA. Although not shown here, we have calculated the input noise current when a series inductor is used as a simple noise matching network, obtaining close agreement with

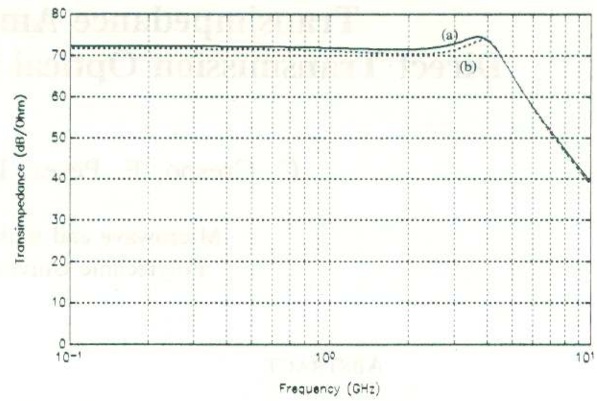

Fig. 2 Transimpedance response of the amplifier Calculated (a) and simulated (b)

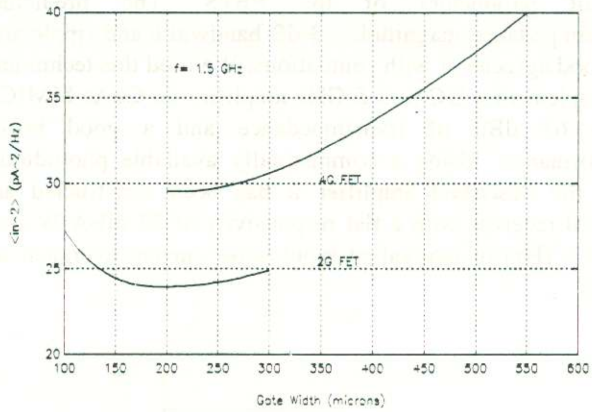

Fig. 3 Cuadratic thermal noise current for 2G and 4G FETs

simulation and it showed the possibility of improve noise performance in the high side of the band.

TRANSIMPEDANCE AMPLIFIER DESIGN

In an initial analysis we substituted the elements of the π-equivalent circuit model for MESFET with the elements of the F20 Plessey process into equations of table 1. It allowed us to select the gate widths of the FETS that optimized the Z_{T0} at low frequencies. The bandwidth of the transimpedance characteristic and the product $Z_{T0}\,f_c$, increases as the feedback resistor decreases, but it implies a ripple increase too. Furthermore the amplifier stability and the equivalent input noise current worsens for low values of the feedback resistor. Making use of the showed equations it has been possible to determinate a near optimum design.

The analysis leads to a first and second FET gate widths of $W1 = 2\times100$ μm and $W2 = 2\times50$ μm, with a feedback resistor of $R_f = 1600$ Ω. In our case to attain a higher transimpedance was necessary to introduce one stage in a common-source configuration for gain and a second buffer for output matching to 50 Ω.

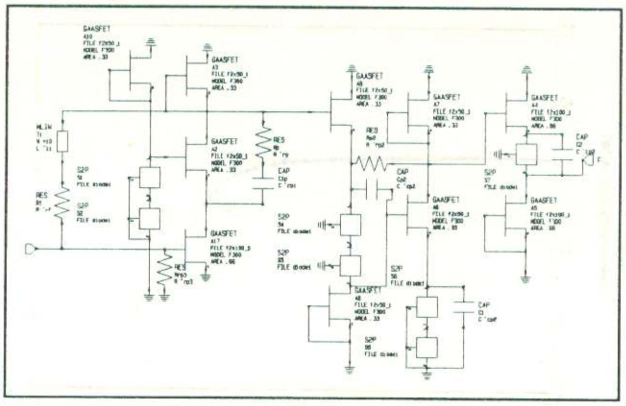

Fig. 4 Basic TIA Schematic

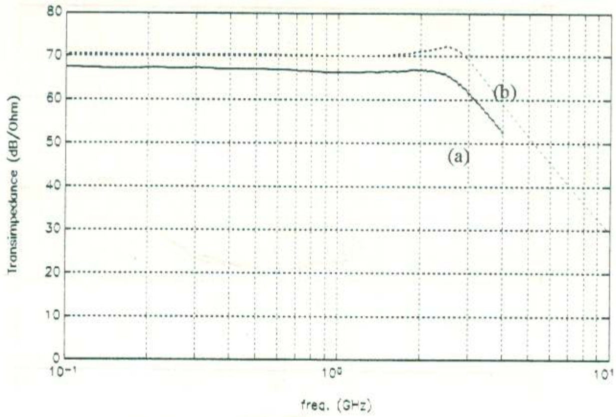

Fig. 6 Transimpedance Measurement (a) and Simulation (b)

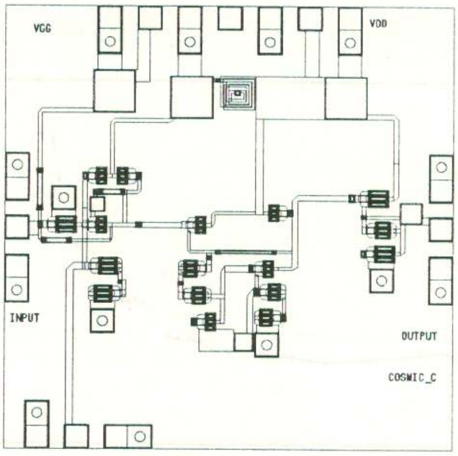

Fig. 5 Final Layout of the Amplifier

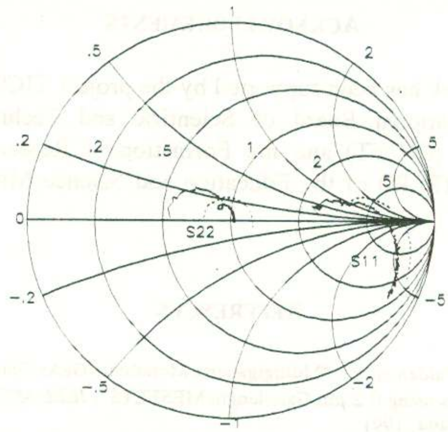

Fig. 7 s_{11} and s_{22} parameters of the TIA Simulation and Measurement

The design was optimized further by simulation with the models of the process components (FETS, resistors, lines, etc.) and completed by making the layout of the circuit. Figs. 4 and 5 show the basic circuit schematic used in simulations and the final layout of the TIA.

MEASUREMENT RESULTS AND CONCLUSIONS

The amplifier s-parameters were measured using techniques described in [11] and the transimpedance characteristic obtained is shown in figs. 6 together with the simulation. It has been measured 67.5 dBΩ for the transimpedance magnitude, a -3 dB bandwidth of 2.7 GHz and a ripple less than ± 0.7 dB. Fig. 7 shows the measured output s-parameter with the corresponding simulation, showing good matching to a 50 Ω load, and the measured and simulated s_{11}. The equivalent input noise current measurement is showed in fig. 8 together with the simulation. The measured noise current with opened input is in good agreement with the simulated one using the model parameters.

The measured transimpedance and the photodiode model were used to simulate the overall responsivity showed with broken line in fig. 9. The responsivity is 40 A/W in the band and as we had expected the photodiode elements lowered the -3 dB cutoff frequency. The measured responsivity of the TIA with a QDE-035C Lasertron photodiode (dots and continuous line) is close to the simulated one, and the difference at high frequencies is due to spurious elements of the assembly, mainly the photodiode parasitic.

The equivalent input noise current density was measured and plotted in fig. 10 with a mean value near 5 pA/√(Hz) in the medium band and a maximum of 9 pA/√(Hz) at the highest frequencies of the band. The simulation (curve a) reproduces without important difference the input noise current dependence, showing the validity of the models used and the analysis performed.

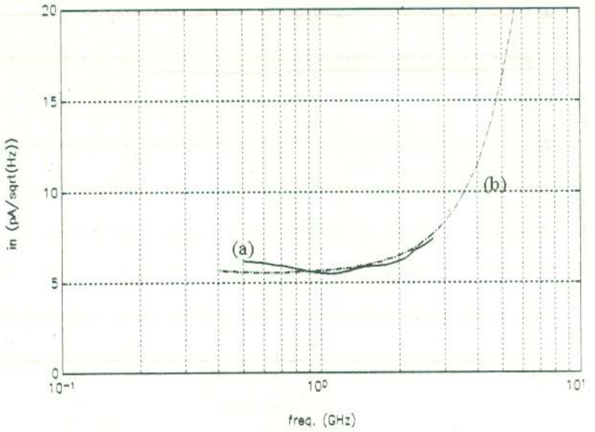

Fig. 8 Equivalent input noise current spectral density
Measurement (a) and simulation (b)

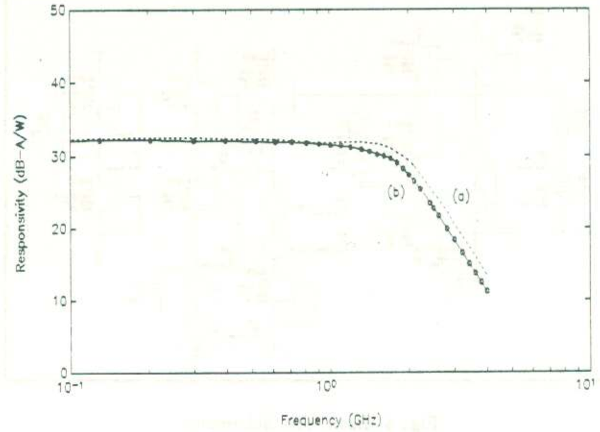

Fig. 9 Responsivity of the optical receiver
Simulation (a) and measurement (b)

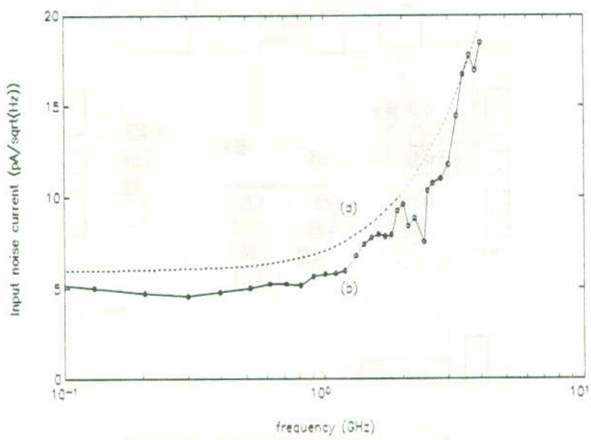

Fig. 10 Equivalent input noise current of the optical receiver
Simulation (a) and measurement (b)

ACKNOWLEDGEMENTS

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