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High Yield Design of MMIC Transimpedance Amplifiers for Multigigabit Optical Transmission Systems

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Abstract

In this paper we present a design methodology for optical receivers based on transimpedance gain stage which reduces the receiver performance sensitivity to the photodiode parameter set. A transimpedance amplifier has been designed following this approach and experimental results are reported which show an improvement in the overall yield of the receiver. The design methodology proposed here has been easily implemented in a microwave simulator.

Introduction

Optical receivers for digital transmission systems require a LNA stage as the preamplifier which has to be optimised to be connected to a capacitive current source (the photodiode). At the input port of the receiver a broad-band current matching has to be obtained, therefore the amplifier should offer a quite low input impedance. The transimpedance amplifier (TZA) is a common topology used to obtain a LNA stage suitable for optical receivers. Among its advantages low-noise capability, high dynamic range and easiness of design must be considered. Unfortunately the feedback used to reduce input impedance becomes less effective as the frequency increases. Consequently the input current matching between the photodiode and the amplifier becomes less favourable. The uncertainty of the photodiode model can reduce the yield of the receiver, if the MMIC amplifier has not been properly designed. Stray capacitances due to the package of the photodiode could reduce the bandwidth, and the designer cannot improve the input matching by reducing the feedback resistor without degrading the noise performance. At the present moment the optical systems which are investigated operate in the MultiGbit data rate range: industrial applications are moving toward 10 GBit/s, whereas research investigation are considering 40 Gbit/s and even higher bit-rates.

Assuming that the bandwidth is approximately equal to three quarters of the data-rate it is apparent the relevance of the coupling between photodiode and the amplifier. Moreover chip on carrier photodiode, which simplify the optical coupling, increase this problem, thus requiring a modelling of the equivalent electrical source.

In an optical front-end the overall gain is defined as the ratio of the output voltage to the short circuit current of the photodiode.

A careful modelling of the coupling between the photodiode chip and the transimpedance amplifier is needed [1]. In Fig. 1 the signal flow is shown: the photo generated current Ig is coupled to the transimpedance amplifier by the interconnection line represented by the scattering matrix SI.

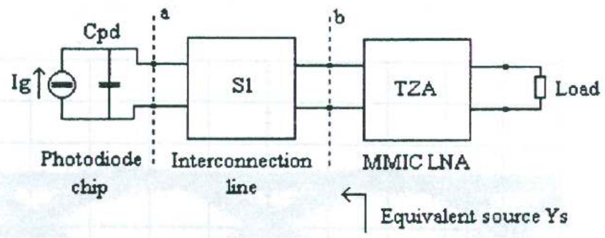

Fig. 1. Signal flow in a optical receiver.

The inteconnection line operates an impedance transformation and at its output port (b) an equivalent source is obtained which is different form the purely capacitive current source available at the chip section (a). An exact characterisation of the equivalent source is quite complex and requires 3D e.m. simulation, therefore it seems to be more promising to focus the attention on the LNA design.

The design methodology

The main purpose of this work is to control the variations of the optical receiver frequency response caused by the parameter dispersion of the optical source by the means of a proper design of monolithic transimpedance amplifier. The design goals can be specified by the following parameters:

d1 - $T(0) > T_{min}$,	Low-frequency gain
d2 - $B_{-3dB} > B_{min}$,	Bandwidth
d3 - $M_r < M_{max}$,	Modulus at the resonance
d4 - $S^{T}_{Y_S} < S_{max}$,	Sensitivity to source admittance

where the specifications d1-d3 concern the eye-diagram opening, whereas the parameter $S^{T}_{Y_S}$ is the sensitivity of the transimpedance gain to the source admittance.

The work which has been carried out can be outlined as follow:

a) find the function to be used in the optimisation step,
b) report the design goals d1-d4 in terms of the chosen optimisation function,
c) implement the procedure on a CAD tool.

In a previous work a simple but effective model for the TZA has been found [2] and the block model obtained is shown in Fig. 2.

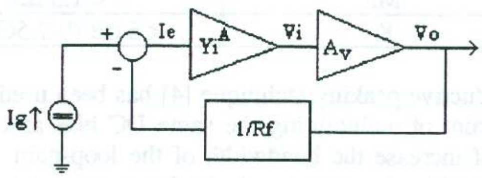

Fig. 2. Block model of the TZA.

The loop gain F is specified by the feedback gain $H^{-1} = \frac{1}{R_f}$, the voltage gain Av and the input admittance Y_i^A of the forward amplifier as follows

$$F = \frac{A_V H}{Y_i^A}. \tag{1}$$

The source admittance Y_S has been included in the input admittance Y_i^A of the LNA since they are in shunt. The transimpedance gain can then be obtained as in Eq. 2 in terms of loop gain:

$$T = H^{-1}\left(\frac{F}{1+F}\right). \tag{2}$$

The design goal d4 can be expressed by using the loop gain as follow:

$$\left|\frac{\Delta T}{T}\right| = \left|\frac{\Delta F}{F}\frac{1}{1+F}\right|, \tag{3}$$

where

$$\frac{\Delta F}{F} = \frac{1}{F}\left[\frac{\partial F}{\partial Y_i^A}\Delta Y_i^A + \frac{\partial F}{\partial A_V}\Delta A_V + \frac{\partial F}{\partial H}\Delta H\right] \tag{4}$$

assuming $\Delta A_V = \Delta H = 0$ for the MMIC amplifier Eq. 4 gives

$$\left|\frac{\Delta T}{T}\right| = \left|\frac{1}{1+F}\right|\left|\frac{\Delta Y_i^A}{Y_i^A}\right| \tag{5}$$

where $\left|\Delta Y_i^A / Y_i^A\right|$ has to be evaluated for the photodiode and the package used [3]. The a priori knowledge of the spread of the source admittance Y_i^A and the desired spread in the transimpedance gain set a bound to the loop gain F. The previously listed specifications d1-d3 which regard the frequency response can be treated by the well-known Nichols plot, and the specification d4 can be added by Eq. 6

$$K = \left|\frac{1}{1+F}\right| \le \left|\frac{\Delta T}{T}\right|\left|\frac{\Delta Y_i^A}{Y_i^A}\right|^{-1}. \tag{6}$$

Therefore a homogeneous set of design goals has been obtained. The design can be oriented to satisfy the specification set d1-d4 by placing the frequency response in the region specified by these constraints. The loop gain F of the TZA can be easily obtained from the open loop transimpedance gain, once the loading effects have been taken into account. The capabilities of the simulator HP MDS have been used to represent the Loop Gain specified by Eq. 1 on a Nichols chart as can be seen in Fig 3.

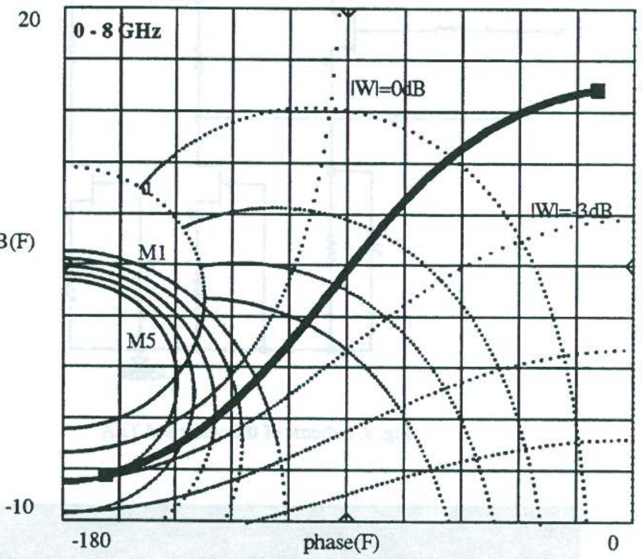

Fig. 3. Nichols plot with constant K loci.

The curves named M1-M5 are constant K loci and refer to the values 0.5 to 4.5 dB increasing in unity steps. The optimisation has to be carried out by moving the frequency points of the loop gain toward regions of the plane which correspond to low-sensitivity circuits. The thick line represent over the bandwidth 0-8 GHz the loop gain of the fabricated amplifier whose design is described in the next section. The design procedure can be summarised as follows:

1) Assign the eye-diagram specifications d1-d3,

2) Evaluate the expected spread of the input admittance of the optical source by measurements or e.m. simulations, then to compute the term $\left|\Delta Y_i^A / Y_i^A\right|$,

3) Assign the desired spread on the overall transimpedance gain $|\Delta T / T|$ and compute the maximum K from Eq. 6,

4) Optimise the forward amplifier by placing the frequency response of the loop gain in the region of the F plane which satisfy the design goals d1-d4.

The design

Following such approach a transimpedance amplifier has been designed using PML D02AH monolithic GaAs process which makes available P-HEMT with $F_T = 62$ GHz. The basic scheme is shown in Fig. 4, and the photograph of the chip in Fig. 5.

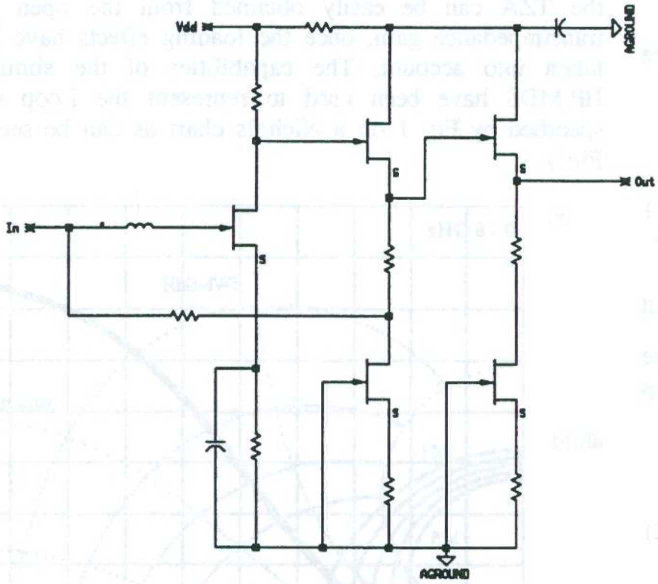

Fig. 4. Scheme of the optimised TZA.

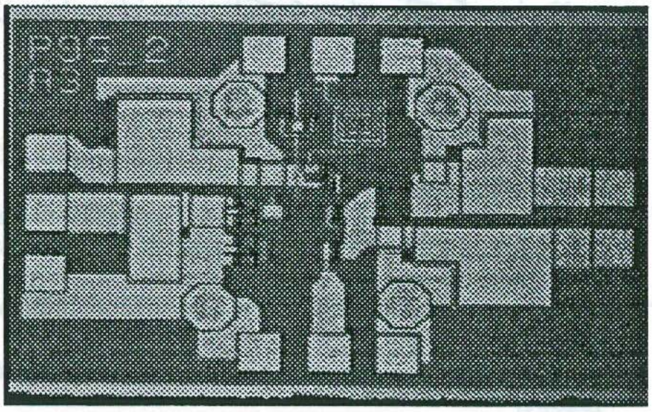

Fig. 5. Photograph of the TZA chip.

The TZA has been designed to be insensitive to the DC spread of the active devices, by using DC source feedback in the gain stage and trimming pads to apply biasing corrections when necessary. The AC optimisation has required a peaking technique in the forward amplifier to satisfy the requirements listed below.

Table 1. Design goals of the TZA.

T(0)	> 52 dB (50Ω loaded)
BW (-3dB)	> 7.5 GHz
Mr	< 1.5 dB
K	< 6 dB (0-7.5GHz)

An inductive peaking technique [4] has been used with the constraint of maintaining the same DC bias and with the goal of increase the bandwidth of the loop-gain. The best compromise in terms of performance and die-area requirements has been found to be an inductor in series with the input port of the forward amplifier. The specifications listed in Tab. 1 has been satisfied. The results of the optimisation has been checked in terms of poles positions of the input impedance and transimpedance gain which are shown in are shown in Fig. 6.

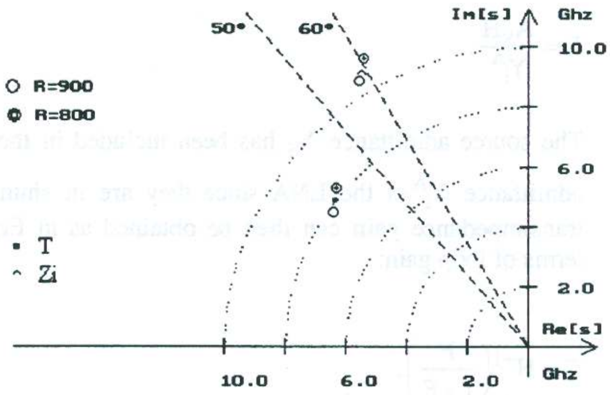

Fig. 6. Root loci of input impedance and transimpedance of the TZA.

The bandwidth of the transimpedance gain is increased by about 4 GHz, and the input impedance remains below 110 Ω up to 10 GHz making easier the coupling with the photodiode.

The chip has been fabricated and tested with Cascade probe station: the DC values coincide with the expected ones and the S-parameters measurements have shown a mismatch with respect to the simulations below 2 dB due to process deviations which have affected the transconductance of the HEMT devices.

A Monte Carlo simulation has been carried out by using the measured scattering parameter of the TZA to check its sensitivity to the dispersion of the optical source. In Fig. 7 the model of the optical source is shown. The junction capacitance and the inductances which model the wire-bonds have been assumed to be uniformly distributed with these deviations Cpd = 0.2±0.05 pF, L = 0.5±0.2 nH.

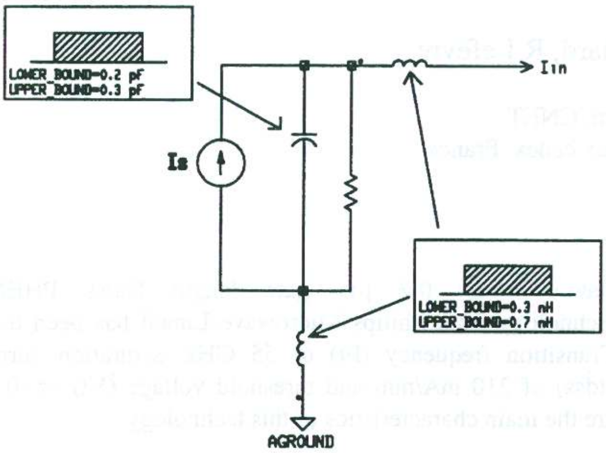

Fig. 7. Model of the optical source used in the Monte Carlo analysis.

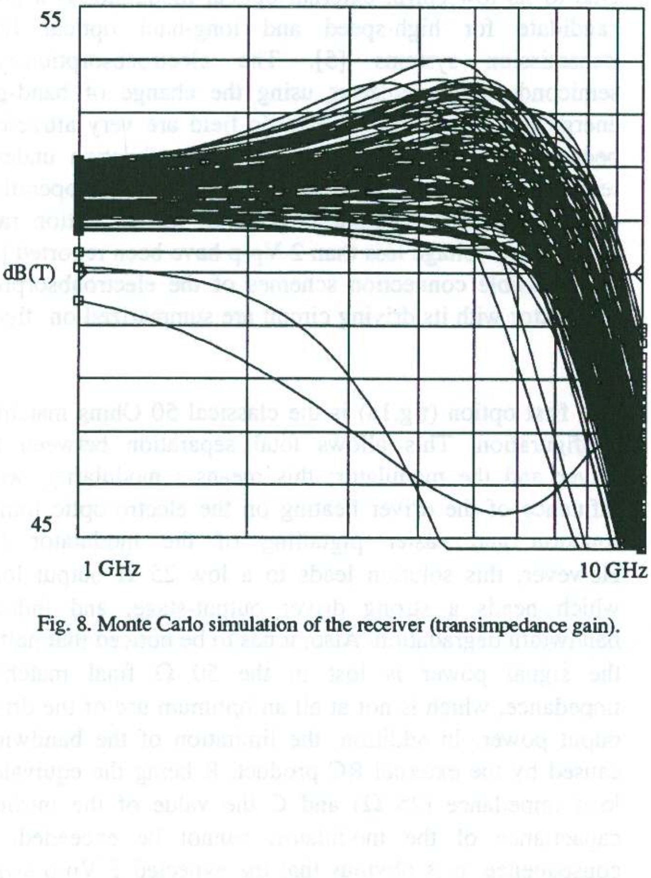

Fig. 8. Monte Carlo simulation of the receiver (transimpedance gain).

The results of the simulation presented in Fig. 8 show a high robustness of the design: the bandwidth deviation remains below 2 GHz and the maximum peaking is below 2 dB. The specification on the peaking is missed probably owing to the lower transconductance of the devices.

Conclusion

In this paper a design procedure for optical receiver which improve the overall yield of the circuit has been presented, assuming that the optimisation of the optical source is often not feasible, the design criteria has been focused on the MMIC LNA. This approach uses the loop gain of the transimpedance gain stage as the optimisation function and reports on a Nichols plot all the design goals. A transimpedance amplifier has been designed by using this approach and a Monte Carlo analysis has confirmed the robustness of the design.

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References

[1] V. Cocco, P. Marietti, A. Trifiletti, "Analysis and reduction of coupling effects between photodiode and the MMIC amplifier in optical receivers," SPIE Proc. Vol. 2401, Functional Photonics Integrated Circuits, San Josè, CA, Feb. 1995.

[2] V. Cocco, P. Marietti, A. Trifiletti, "A new design approach for monolithic transimpedance receivers based on root-locus technques," Microwave and Opt. Lett., Vol. 7, No. 15, Oct 20 1994.

[3] T. S. Tan, C. Kocot, J. Staznicky, R. T. Kaneshiro, F. Keller, "A high-speed flip-chip PIN photodetector with integrated micro-lens," SPIE Proc. Vol. 2149, Tech. for Optical Fiber Comm., Los Angeles, Jan 1994.

[4] N. Ohkawa, "Fiber-optic multigigabit GaAs MIC front-end circuit with inductor peaking," Jour. Light. Tech., Vol. 6, No. 11, Nov. 1988.