GAAS® 97 • 5th European Gallium Arsenide and related III-V compounds Applications Symposium
Bologna, Italy - September 3rd-5th, 1997

Optimisation Criteria of Band-Pass Matching Networks for Optical Receivers in Microwave Optical Links

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Abstract - In this paper we present a criterion for the optimisation of tuned optical receivers which can be useful in narrow band systems applications. The design goal for the input matching network has been found by minimising the input equivalent noise current setting as a constraint a constant transimpedance gain for the overall receiver. Exact formulas for the input impedance of the matching network and the penalty for detuning are provided for a single frequency together with a finite bandwidth application case study.

Introduction - Narrow-band optical systems are becoming more and more important owing to the need of low-loss bandpass transmission channels (CATV AM-SCM systems, microwave links for Radar systems). In these applications the bandwidth requirements are quite moderate (i.e. BW<1GHz) with respect to the capability of the optical fibre. The sensitivity of narrow-band receivers can be greatly increased taking into careful consideration the impedance matching conditions at the input port of the amplifier. One of the basic problems that arises in the design of optical receivers operating in the GHz range, is to match an intrinsically high impedance source, the photodiode, to a microwave amplifier which requires low source impedance to get maximisation of its power gain and noise figure minimisation.

A design technique that is usually followed, is to place a lossless matching network between the photodiode and the amplifier. This network must be designed as a band-pass filter so the amplifier is feeded by a driving point impedance that permits maximum power transfer and minimum noise figure. These two conditions usually cannot be both fulfilled [1], besides it is necessary to fix a non-zero bandwidth and a given transimpedance gain (output voltage over input photocurrent).

In this work we demonstrate how it is possible to design the matching network so that the overall receiver performance is optimised in terms of minimisation of input equivalent noise current for a fixed transimpedance gain. In particular we define a criterion to optimise the noise performance for a single frequency (under the constraint of a fixed gain) and we find the design goal to be set to the lossless equaliser to obtain this optimum condition. Therefore the design can be carried out by optimisation of the lossless equaliser, regardless of the following amplifier, either by using a Real Frequency technique [2] or by using the optimiser of a circuit simulator.

Moreover, we have obtained the performance degradation following a detuning with respect the optimum impedance, which can be useful in a finite bandwidth application.

Finally we present the results of a case study of equaliser synthesis in the bandwidth 400-800 MHz.

Optimum Criterion and Design Goal - In tuned optical receivers optimisation, a design methodology based on a theoretical approach has not been found yet. In fact, a usually followed but erroneous way to optimise optical receivers performance is to match the output network impedance to the optimum noise figure impedance of the first stage of the amplifier. As pointed out by Haus in his classical work [3], in case of stated overall receiver gain, it is necessary to adopt more than a single stage. It follows that, the optimisation of the first stage noise figure by the optimum noise figure impedance, does not mean to optimise the overall noise performance. For example, if we have a two stages amplifier, the first stage should be the one with lowest quantity $M = \frac{(F-1)G}{G-1}$, defined following Haus as "Noise Measure", that could be not the one showing the lower noise figure. It is reasonable to think that, as it will be shown in this work, a trade-off exists between power-matching and noise minimisation when bandwidth and transimpedance gain are fixed. In a previous work [4] we have made a comparison between power and noise matching approaches, but we didn't find the optimum reflection coefficient to be set for the equaliser, as we are going to do in this work. The amplifier shown in Fig. 1 is thought to be a cascade of the same gain stages whose parameters are:

$$\{NF_{MIN}, Y_{OPT}, R_N\}, \tag{1}$$

$$\{Y_{11} = Y_{11}(\omega), Y_{12} = 0, Y_{21} = Y_{21}(\omega), Y_{22} = 1/50\Omega\}. \tag{2}$$

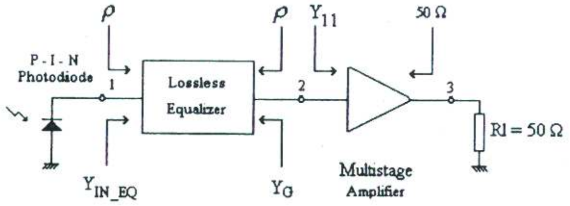

Fig. 1. Block scheme of the tuned receiver.

We have assumed the unilateralness and the perfect output matching of the single gain stage as they are well approximated by commercially available MMIC amplifiers [5]. The photodiode has been modelled by an ideal current source with a parallel resistor-capacitor output impedance. The optimisation criterion proposed here is the minimisation of the noise figure of the amplifiers chain with a fixed transimpedance gain of the over-all receiver. For each value of the output impedance of the matching network a transimpedance gain of the matching network is set. Therefore the voltage gain of the amplifier must be varied accordingly in order to ensure the specified transimpedance gain. This is obtained by considering a chain of more than one amplifier and taking into account the noise contribution of the first two stages. The noise figure of the cascade of two amplifiers is given by Friis's formula:

$$NF_{12} = NF_1\left(Y_G\right) + \frac{NF_2\left(Y_{22}\right) - 1}{G_{AV1}} \tag{3}$$

where G_{AV1} is the available power gain of a gain stage; under the assumption of the parameter sets (1, 2), Eq. 3 can be written as follows:

$$NF_{12} = NF_{MIN1} + R_N f\left(G_G, B_G\right) \tag{4}$$

and by separating the constant term from the variable part it is possible to find the function to be minimised:

$$f\left(G_G, B_G\right) = \frac{1}{G_G}\left|Y_G - Y_{OPT}\right|^2 + \frac{NF_2\left(Y_{11}^*\right) - 1}{R_N G_{AV1}^{MAX} \dfrac{G_G}{\left|Y_{11} + Y_G\right|^2}} \tag{5}$$

where power matching between the amplifiers has been assumed and G_{AV1}^{MAX} is the maximum available gain of the gain stage. We have found the following value for the output impedance of the matching network $\hat{Y}_G = \hat{G}_G + j\hat{B}_G$ which minimise the input equivalent noise current:

$$\hat{G}_G = \sqrt{\frac{G_{OPT}^2 + c' G_{11}^2 + \dfrac{c'}{1+c'}\left(B_{OPT} + B_{11}\right)^2}{1+c'}} \tag{6}$$

$$\hat{B}_G = \frac{2\left(B_{OPT} - c' B_{11}\right)}{1+c'} \tag{7}$$

where c' is given by:

$$c' = \frac{NF\left(Y_{11}^{*}\right)-1}{G_{AVI}^{MAX} R_N} \tag{8}$$

Since the input noise equivalent current is a useful parameter in optical applications by using the condition that the noise figure is unchanged by lossless transformations [6] we can get the final expression of Ieq:

$$I_{eq} = (NF_{12}-1)\,4kT\,\mathrm{Re}[Y_{PD}] \tag{9}$$

as a function of the output admittance of the photodiode Y_{PD}.

Noise Circles Representation - Further investigations aimed to analyse the performance degradation due to detuning have been performed. In particular the Eq. 5 can be written as follows:

$$f(G_G, B_G) = f_{min}\, P(G_G, B_G) \tag{10}$$

where f_{min} is the minimum value of f and $P \geq 1$ is a penalty factor. The noise performance can be represented by a set of constant Noise Figure circles specified by their centres and radii R(f) as functions of $f = f_{min}P$.

$$G_G(f) = \frac{\left(\frac{1}{2}\right)f + G_{OPT} - c'\,G_{11}}{1+c'}, \tag{11}$$

$$B(f) = \hat{B}_G \tag{12}$$

$$R(f) = \frac{1}{1+c'}\left[\begin{array}{l}\frac{1}{4}f^2 + (G_{OPT} - c'\,G_{11})f + \\ \\ -c'\left[2(G_{OPT}G_{11} + B_{OPT}B_{11}) + G_{11}^2 + B_{11}^2 + G_{OPT}^2 + B_{OPT}^2\right]\end{array}\right]^{0.5} \tag{13}$$

Design Methodology - In system applications a power sensitivity level of the receiver is set, thus for each frequency a maximum value of the penalty P can be easily obtained. From the Eqs. 11-13, the requirements to be set to the matching network are obtained in terms of Noise Circles parameters. By complex normalisation (Youla [7]) these parameters can be converted in a maximum value imposed to the modulus of the reflection coefficient of the matching network. Then a standard network synthesis technique can be used to design the matching network [2,8], and the number of degrees of freedom of the optimisation problem can be greatly reduced.

A case study - In order to check the noise performance degradation in a finite bandwidth application we have optimised an equaliser, made by a ladder of lossless LC elements, for the receiver topology shown in Fig. 1. The single gain stage of the amplifier is a commercially available Si MMIC, the AVANTEK INA-02170. The average equivalent noise current over the bandwidth 400-800MHz is 1.135pA/√Hz. The noise performances have been compared with 2 different ideal cases. Firstly we have calculated the minimum input noise current Ieq_{min}, obtained with noise input matching at each frequency. Much more interesting is the comparison with Ieq_{opt}, which represents the input equivalent current noise corresponding to a reflection coefficient ρ calculated with the Bode-Fano theory as in [4]. The effects of detuning on noise performances have been reported in Fig. 2. In Fig. 3 is reported the transimpedance gain of the receiver.

Conclusions - In this paper an optimisation criterion for band-pass optical receivers has been found, and a clear design goal to be set to the matching network has been obtained.

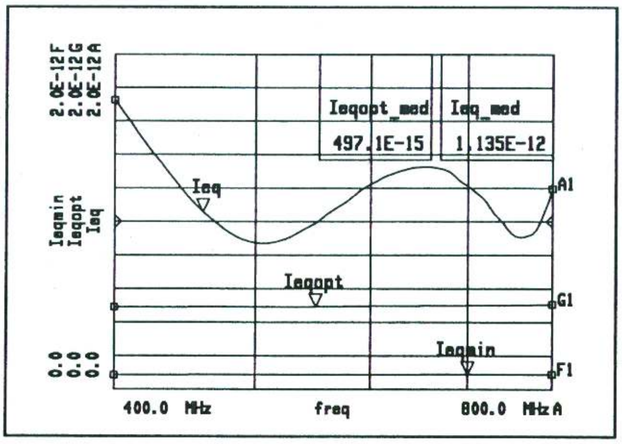

Fig. 2. Comparison among the equivalent noise current of the receiver (Ieq), the noise current limit given by the Bode-Fano theory (Ieq$_{opt}$), and the minimum noise current (Ieq$_{min}$).

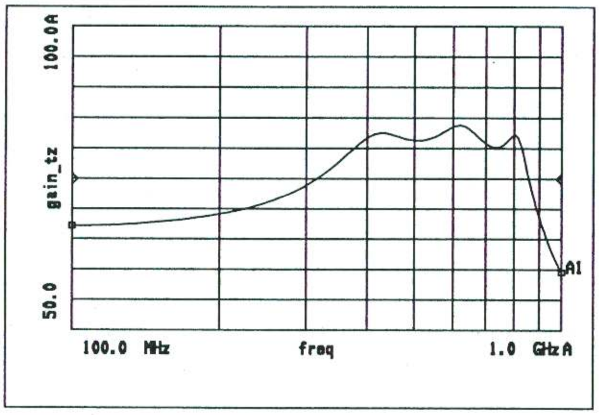

Fig. 3. Transimpedance gain (dBΩ) of the receiver.

For a given photodiode and amplifier chain the sensitivity limit has been found for each single frequency. The noise performance degradation due to detuning condition has been analysed in terms of noise circles representation. Then these analytical results has been effectively used in a worked example of matching network synthesis and the equivalent noise current of the receiver has been compared with the minimal value obtainable at each frequency and with the minimum value obtained in a finite bandwidth with Bode-Fano limit.

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