Increasing Sensitivity of Optical Receivers using a Divide-and-Conquer Technique

Guillermo Royo, Antonio-Dionisio Martínez-Pérez, Concepción Aldea Chagoyen, Santiago Celma

Afiliation: Grupo de Diseño Electrónico
Instituto de Investigación en Ingeniería de Aragón (I3A)
Universidad de Zaragoza, Mariano Esquillor s/n, 50018, Zaragoza, Spain.
Tel. +34-976762707, e-mail: royo@unizar.es

Abstract

This paper presents a noise-reduction technique to increase the sensitivity of optical receivers with large integrated photodiodes (PD). It consists of manufacturing the PD in several pieces and connecting each piece to a dedicated transimpedance amplifier (TIA). The output signals are combined achieving a better sensitivity and a higher transimpedance.

Introduction

Large area photodiodes (1-mm diameter or more) are used in many instrumentation and communication applications. For example, plastic optical fiber (POF) sensors are a new class of fiber sensors used in oil, gas, biotechnology, and energy fields. Thanks to the POF's large diameter and the inexpensive peripheral components and low installation costs, many electronic equipments are built based on POF and photodiodes (PDs) with a large active area, such as a sensor for oil trucker valve monitoring, a monitoring system for high voltage substation switch, an oil leaking sensor for offshore platforms, and a solar tracker for illumination. To interface such PDs and overcome the high attenuation of POF, a low-noise TIA must be designed. The most-commonly employed TIA configuration is the shunt-feedback topology, shown in Fig. 1, due to its better linear performance and ease of design. Achieving high sensitivity to increase the maximum transmission length and throughput is one of the most important challenges, and several noise-reduction techniques have been described in the literature [1]. In this work, we propose a technique that consists of slicing the PD and manufacturing it in N individual pieces, connecting a dedicated TIA to each of them, as shown in Fig. 2. Analyzing the feedback-TIA circuit we can obtain the input-referred noise expression (1), in which we see that the input-referred noise is strongly dependent on the PD capacitance, C_{PD}, which also limits the maximum achievable transimpedance with a trade-off bound to the transimpedance limit [2].

$$i_{n,in}^2 \approx \frac{4K_BT}{R_F} + \frac{v_{n,A}^2}{R_F^2} + v_{n,A}^2\omega^2C_{PD}^2 \qquad (1)$$

$$R_T \leq \frac{A_0\omega_A}{C_{in}BW^2} \qquad (2)$$

where K_B is the Boltzmann's constant, T the temperature, R_F the feedback resistor of the TIA, A_0, $v_{n,A}^2$ and ω_A the open-loop gain, input voltage noise and first pole frequency of the core voltage amplifier, respectively, and BW the 3-dB bandwidth of the TIA. With the proposed technique, each piece of the original PD presents a parasitic capacitance, C'_{PD}, $1/N$ times lower than C_{PD}. Therefore, from (1) we can expect a lower input noise and, from (2), a greater transimpedance should be achieved. To keep a constant R_FC_{PD} product, the feedback resistor is multiplied by N. If we calculate (1) with the new parameters, adding the contribution of the N TIAs:

$$\begin{aligned} i_{n,in}^2 &= \sum_1^N \frac{4K_BT}{NR_F} + \frac{v_{n,A}^2}{N^2R_F^2} + \frac{v_{n,A}^2\omega^2C_{PD}^2}{N^2} \\ &= \frac{4K_BT}{R_F} + \frac{v_{n,A}^2}{NR_F^2} + \frac{v_{n,A}^2\omega^2C_{PD}^2}{N} \qquad (3) \end{aligned}$$

We obtain a significant reduction of the f^2 noise contribution, which shows a $1/N$ dependence, thus a better signal-to-noise ratio can be achieved.

Results

Let us now apply the sliced photodiode technique to an actual feedback TIA design. The configuration employed to perform the simulation is a TIA structure which consists of three cascaded common source stages with a negative resistive loop. The circuit has been implemented in a 65-nm CMOS technology with a single 1.2-V voltage supply. To

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model the PD, we have used the PD parameters reported in [3], that is C_{PD}=14 pF and a responsivity of 0.42 A/W at 850 nm. As the main purpose of this paper is to demonstrate the feasibility of the sliced PD technique, we have chosen a BW of 1 GHz, for which we have optimized the TIA design, achieving a maximum sensitivity of -11.0 dBm. In this work, the sliced PD technique has been applied dividing the PD in N pieces, choosing powers of 2 for the values of N, up to 16 [4]. Fig. 4 shows the equivalent input-referred noise response, clearly exhibiting a drastic decrease of the spectral density at high-frequencies for higher N values. Table 1 summarizes the key performance parameters of the front-end obtained by slicing the PD in different number of pieces. There is a remarkable increase of the sensitivity, from -11.0 dBm using the traditional single-PD approach to -15.8 dBm by slicing the PD in 16 pieces.

Conclusions

A novel optical front-end design technique has been presented in this paper. It consists of slicing the photodiode area and connecting a TIA to each piece, instead of the conventional approach of a single-piece PD. The results show that the sensitivity is improved while maintaining the bandwidth and the achieved transimpedance can be much higher when the technique is applied dividing the PD in a high number of pieces.

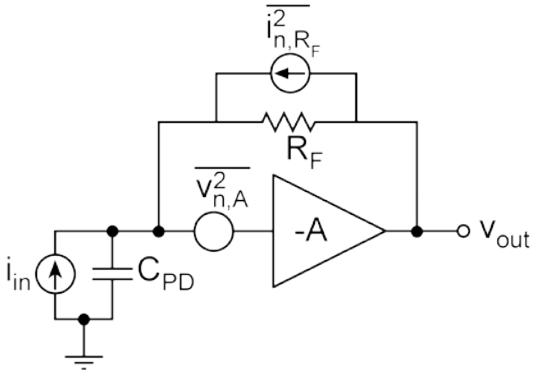

Fig. 1. Schematic diagram of a shunt-feedback TIA including noise sources.

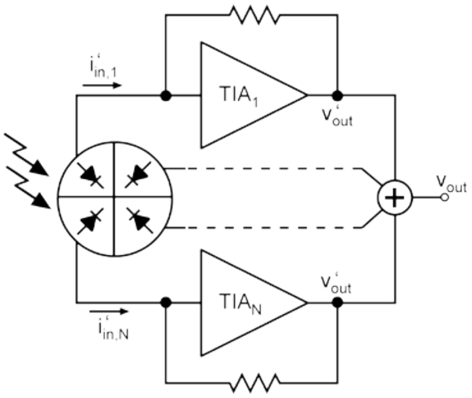

Fig. 2. Conceptual scheme of an optical front-end using the sliced-PD technique with *N* pieces and *N* TIAs.

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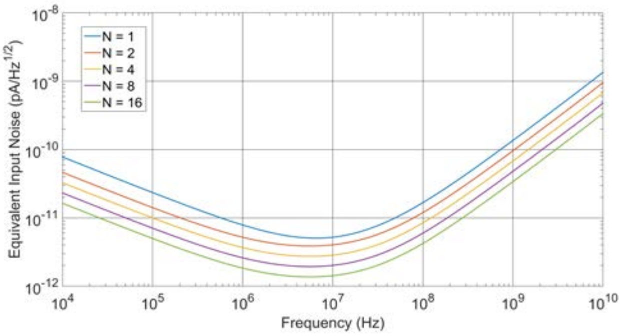

Fig. 3. Input-referred noise of the front-end using the sliced-PD technique for different number of pieces.

Table 1. Summary of the simulation results using the sliced-PD technique with different number of slices.

Parameter	N=1	2	4	8	16
R_T (dBΩ)	75.7	75.7	75.8	75.8	75.7
BW (GHz)	1.02	1.20	1.31	1.34	1.35
Input RMS Noise (μA)	4.74	3.89	2.57	1.89	1.58
Sensitivity (dBm)	-11.0	-11.8	-13.7	-15.0	-15.8
Power (mW)	2.9	5.8	11.5	23	46