DESIGN TECHNIQUES FOR HIGH PERFORMANCE OPTICAL WIRELESS FRONT-ENDS

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1 ABSTRACT

Wireless optical networks usually have demanding specifications in terms of bandwidth, dynamic range and sensitivity. The front-end is a critical element for the fulfillment of these demands. This paper discusses several design aspects of front-ends for optical wireless communications, covering techniques for achieving high gains, high input dynamic ranges, improving noise performance, and reducing electromagnetic interference (EMI). The paper further presents some experimental results of many of the techniques here described. The cumulative usage of those techniques significantly increases system performance, in terms of sensitivity, power and bandwidth even with low cost, CMOS technologies.

2 INTRODUCTION

Two major technologies have been used for wireless communications in the last years: radio and optical infrared. The major advantages of the optical systems over radio solutions are: i) optical systems are virtually free from radio and microwave noise; ii) optical systems inherently provide high security; and, specially, iii) optical systems are free from spectrum restrictions. Wireless optical systems can be currently found at the heart of most remote control systems (e.g. the IrDA standards), telemetry applications, and short range communication systems (like headphones, mobile phones, computer applications and many more).
Designing a optical wireless communication system is a multidisciplinary task [1, 2], covering areas so diverse as optics, material sciences and electronics. Basically, there are three different system components: the emitter, the optical channel and the receiver. The optical channel poses severe restrictions to system components, namely: i) defines the optical power level at the output of the emitter; ii) imposes the necessary sensitivity and input dynamic range of the receiver front-end; iii) and impact the architecture of the receiver.
The receiver is responsible for the optical power conversion and signal processing: a PIN photodiode converts the optical signal into an electrical current, which is further amplified by a front-end amplifier. The output signal is then processed by a digital unit [1-3]. The front-end plays an essential role in the design of the receiver, because it impacts the overall sensitivity, bandwidth and dynamic range. This paper discusses design problems in specific front-ends for wireless LANs. In particular, this paper addresses diffuse LANs, where all terminals have to fulfill stringent emitting power limitations, handle ambient light noise, and handle optical path variations. A further problem for diffuse networks is the pressure for low cost designs, pointing to the use of low-cost CMOS technologies which can facilitate the integration of the front-end in the overall receiver. Another restriction is originated from the photodiodes, as for mass-market systems, low cost photodiodes should be used. Due to power limitations the photosensitive area of these photodiodes should be large, which imposes large intrinsic capacitances at the front-end input, resulting in limitations on the front-end bandwidth.

3 FRONT END TOPOLOGIES

There are three different architectures (Fig. 1) for the design of amplifiers suitable to digital communications: i) the small impedance amplifier, ii) the high impedance amplifier and iii) the transimpedance amplifier [2, 3]. Transimpedance amplifiers are usually preferred mainly because they can overcome the major drawbacks of each of the other two architectures (low sensitivity in low impedance amplifiers, and limited bandwidth in high impedance amplifiers), while keeping their most attractive features (high bandwidth with small input impedance, and high sensitivity with high gains).
Recently, current-mode techniques are suggesting an alternative architecture for front end design [6, 10], using current-mode matching devices (CMD) between the photodiode and the transimpedance amplifier (Fig. 1c), and reducing the input impedance of the transimpedance configuration, thus improving bandwidth. Other features that can be implemented with these CMDs may include automatic gain control schemes [4], or common-mode noise reduction.

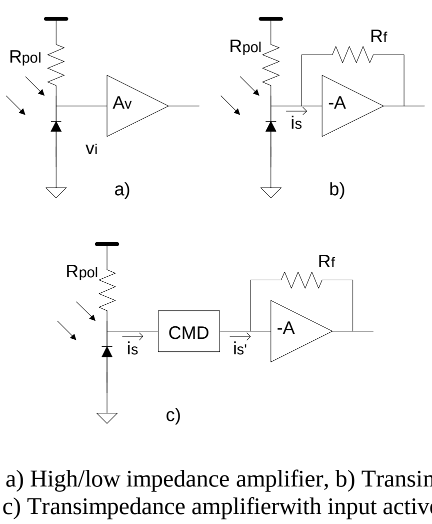

Figure 1 a) High/low impedance amplifier, b) Transimpedance amplifier, c) Transimpedance amplifierwith input active matching

Table 1 Comparison between published front-end characteristics

Ref.	Architecture		Features					
	Type	AGC	Max. Gain (KΩ)	BW (MHz)	DR (dB)	<ieq> (pA/√Hz)	Cpin (pF)	Power (mW)
4	Diff.	Dyn.	19	70	77	6,7	5	8
5	Sing.	Dyn.	3500	50	60	1,13	3	500
6	Diff.	Dyn.	335	170	80	6	<3	37,5
7	Sing.	Fix	1	500	…	7	<0,8	25
8	Diff.	Switch	400	20	80	1,9	10	55
9	Diff.	Dyn.	400	50	60	8,2	10	60

Table 1 makes a comparison between state of the art front-ends regarding different performance criteria, including the gain, bandwidth, power, equivalent input noise, and architecture. Different topologies were analyzed: single ended front-ends [5, 7], differential front-ends [4, 6], and front-ends with CMDs [6]. Next section discusses several design techniques for state of the art front-ends that can be used to achieve improvements in one performance aspect, without compromising the others.

4 DESIGN CHALLENGES

4.1 Dealing with EMI

Electromagnetic interference (EMI) is a common source of noise in electronic systems. EMI is caused by surrounding electronic equipment and disturbs the normal operation of highly sensitive circuits (like transimpedance front-ends). EMI can be reduced using the following strategies: i) appropriate shielding of the susceptible parts of the receiver; and ii) using differential structures for all the critical circuits as depicted in fig. 2. Fig. 2a shows a fully differential transimpedance amplifier: the input signal is applied to both its inputs using the same photodiode. The main advantage of this strategy, is the possibility of reducing EMI disturbances at the input stage, but has the drawback of employing, differential transimpedance amplifiers with high common mode rejection ratios (CMRR), difficult to design. Pseudo-differential structures (as in fig. 2b) have the advantage of avoiding the high CMRR requirement of differential structures. The input stages provide equal gain paths, with phase opposition provided by the photodiodes. The differential amplifier (with high CMRR), effectively rejects the signal common-mode components.

4.2 Reducing Optical Noise

When using a photodiode to detect optical signals, the generated photocurrent consists of two components: i) the signal current (proportional to the incident optical power); and ii) a noise component. Noise sources in a photodiode have different origins, namely: thermal noise, shot noise and optical excess noise. Thermal and shot noise contributions are considered white noise sources with small spectral density, while optical excess noise has its power concentrated in the

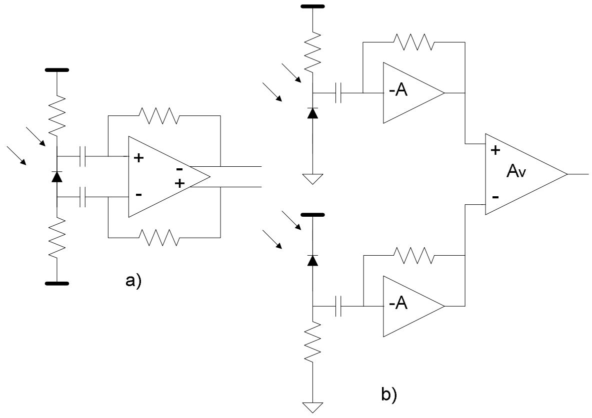

Figure 2 Front-end design handling common mode noise a) Differential amplifier, b) Pseudo differential amplifiers

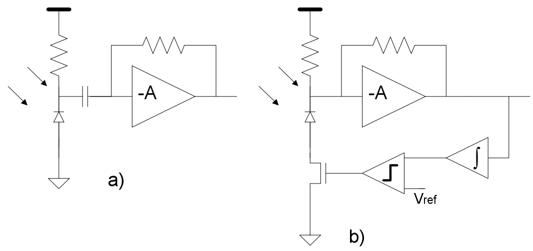

Figure 3 a) High-pass filtering, b) Dynamic biasing

low frequency range. This advises the use of high-pass filtering at the input of the front-end, as represented in both fig. 2a and 3a. This high-pass filtering can be realized using the photodiode bias resistor together with a bypass capacitor. However this technique is unsuitable for integration, as it requires large areas to implement the desired capacitor.
An alternative design suitable for integration, applies a dynamic biasing scheme to the photodiode [4]. The effect of optical excess noise can be regarded as random fluctuations with a magnitude 100 times superior to the magnitude of the detected signal [4]. It is possible to eliminate these fluctuations using an error amplifier to detect the output average-level and then subtract (using a controlled current source as shown on fig. 3b) it from the input, thus removing the noise component from the total generated photocurrent.

4.3 Electronic Noise Optimization

Thermal noise is the dominant noise source in MOS transistors, being dependent on two design parameters: bias condition and transistor dimensions. Increasing transconductance in MOS transistors, results in improvements on both frequency performance thermal noise contributions. However, due to the existence of the photodiode capacitance, the noise minimization problem is slightly more complex. Criteria for defining an optimum value for the design ratio of the input transistor in a transimpedance amplifier have been established [2]. Assuming that the input transistor has minimum length and

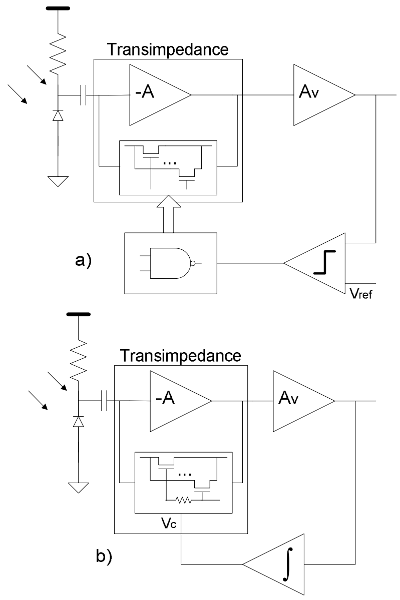

Figure 4 a) Switched gain strategy b) Contolled feedback strategy

maximum bias current (resulting in high transconductance transistors with small parasitic capacitances), the optimum width of this transistor is set in order to match the total amplifiers' input capacitance to the photodiode intrinsic capacitance C_p [2] and is given by,

$$W_{opt} = \frac{C_p}{C_{ox}L} \quad (1)$$

Where C_{ox}, is the oxide capacitance per unit area from gate to channel. The optimum width for the case where both noise and bias current need to be optimized, as in front-ends for low-power applications, is one third of the previous value [2].

4.4 Gain versus Dynamic Range

There are two quantities which bound the dynamic input range: i) the front-end sensitivity - the minimum signal that can be recognized considering the presence of noise; ii) and the maximum output signal for which the front-end still exhibits an approximately linear response – strongly affected by the supply voltages.

To achieve both high sensitivity and high input dynamic range the transimpedance gain can not be fixed, and should be adapted to the input signal. Unfortunately, controlling the transimpedance gain while optimizing noise performance, for the typically high sensitivityof these amplifiers, may turn to be a difficult task to accomplish. Two strategies have been implemented to circumvent this problem: i) a switching feedback scheme, (fig. 4a); and ii) a controlled feedback scheme (fig. 4b).

The switched gain strategy consists in a transimpedance amplifier with a switched feedback network [9]. The transimpedance gain is selected according to a set of previously defined thresholds. If the output level increases (decreases) above some specified limit, the decision circuitry acts on the feedback network in order to decrease (increase)

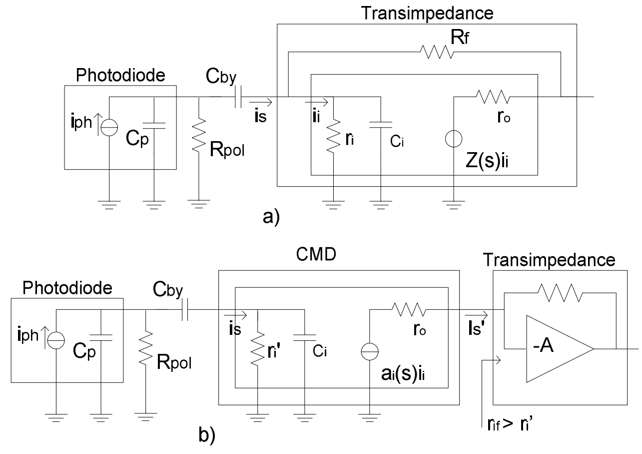

Figure 5 Small signal model a) without CMD, b) with CMD

gain. The number and magnitude of the different gains are set to meet the required sensitivity and the required input dynamic range. The overall performance is limited by the design of the front-end with larger gain. This strategy has some shortcomings: i) the required system bandwidth must be met with all different gains; ii) the switching scheme must act with a carefully designed time constant in order to prevent both oscillations or signal losses during gain switching.

Some of these disadvantages are overcome using a dynamic gain control scheme. The control circuit acts proportionally to the signal level, varying a set of multiple feedback resistors in order to obtain an easily controlled gain. This control scheme operates in such a way that it is effectively outside the signal path for the largest gains, achieving the lowest internal noise for very low input signals. An advantage of this scheme over the switched approach strategy is the inherent automatic gain control action on the output signal. Furthermore, the absence of the switching unit makes this strategy less prone to oscillatory behaviors.

4.5 Bandwidth Maximization

Maximizing bandwidth in transimpedance amplifiers often relies in one of following procedures [2]: i) using more expensive technologies with faster transistors, such as SiGe or BiCMOS; ii) increasing the bias current for the transistors in the first amplifying stage; iii) using smaller intrinsic capacitance photodiodes. The last two procedures produce the same net effect: the reduction of the total input capacitance, while the first one is usually precluded by cost and integration motivations.

Fig. 5a shows the small signal equivalent of an optical wireless amplifier, with an input photodiode connected to a transimpedance front-end. The transfer function of this circuit [3] is given by equation (2):

$$\frac{V_o}{I_{ph}} \approx \frac{sR_{pol}R_iC_{by}}{1+s\left(R_i\left(C_{by}+C_p\right)+R_{pol}\left(C_{by}+C_i\right)\right)+s^2R_{pol}R_iC_T}A_v \quad (2)$$

Where C_T is $C_{by}C_i$+C_iC_p+$C_{by}C_p$, R_i is defined as an approximation by the parallel of ri and R_f and A_v represents the voltage gain (given by $Z_f(s)/R_i$). Equation (2) reveals the

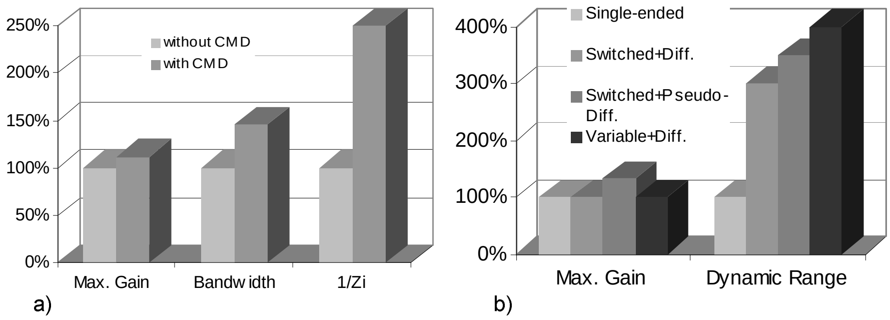

Figure 6 Experimental results a) bandwidth improvements, b) dynamic range improvements (gain scales are in logarithmic units)

pass-band effect caused by the front-end input network, revealing two cut-off frequencies: the low cut-off frequency may be explored to reduce the optical excess noise; the high cut-off frequency is in general established [2, 3] by the product of the total input capacitance to the front-end input impedance. It is possible (although not simple) to increase the front-end bandwidth decreasing the transimpedance amplifier's input impedance.

Current matching devices (CMD) can introduce some advantages on the design of transimpedance amplifiers, especially on this input impedance problem. Several contributions [4, 6, 10] employ an active matching device between the photodiode and the amplifier, with the purpose of reducing its input impedance [6, 10] or to provide some gain control [4, 6]. The CMD usually acts as a current amplifier with small input impedance. Fig. 5b shows a small signal model of this amplifier configuration. The overall transfer function is now ruled by a modified equation (2) using $a_i(s)Z_f(s)/r'_i$ instead of A_v. As r'_i is designed to be much lower than the amplifier's input impedance, the resulting system bandwidth is improved.

5 EXPERIMENTAL RESULTS

The techniques explained in the previous section were evaluated in several front-ends, most of them manufactured (with a standard 0.8μm CMOS process) and tested. For comparison of the different advantages of those design techniques, different designs employed different strategies, and were confronted with a reference transimpedance amplifier, with 112dBΩ gain, 50MHz bandwidth and 20dB dynamic range, using small cost photodiodes with C_p=10pF.

Fig. 6a demonstrates the bandwidth benefits due to the use of a CMD between the photodiode and the reference transimpedance amplifier. Using this technique, the attained bandwidth showed an almost 40% increase, due to a noticeable reduction in the input impedance, even without optimization of the reference amplifier. An added advantage is the increase on transimpedance gain, by the exact amount of the gain provided by the CMD (almost 12%).

Dynamic range results are presented in fig. 6b, for three different front-ends. The reference circuit uses a single-ended topology with small input dynamic range, while all the other front-ends use differential or pseudo-differential topologies and variable or switched gain schemes. It is apparent that the variable gain front-end has the largest input dynamic range.

6 SUMMARY AND CONCLUSIONS

This article presented an overview of design solutions for high performance optical wireless transimpedance amplifiers. Strategies for high bandwidth, high gain and high immunity achievements in this kind of amplifiers have been discussed, presenting several alternatives. We analysed some results we achieved with many of these techniques, and presented other state-of-the-art results for confrontation. Considering the multiple requirements on front-ends for optical wireless applications, with high input dynamic range, high gains, low noise, and large bandwidth requirements, the best design strategies seem to rely on differential architectures with variable gain capabilities integrated. Current-mode approaches can also provide interesting alternatives in more complex designs.

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