Conclusions

After the free fall of the telecommunication industry in the beginning of this century, a gradual recovery started in 2004. At the end of 2006, this positive evolution continues and people start to dream again. Numerous new opto-electronic applications are emerging, while low cost remains a prime concern. The simple law of economics dictates that the existing III-V compound semiconductor opto-electronics industry will be affected by optical devices made of silicon. Nowadays, silicon devices can achieve almost all of the necessary functions for integrated optical devices, like detectors, modulators and switches. Only an electrically powered silicon light source, preferably a laser, is lacking, although successful research is going on also in this field, for instance by Intel [CP06, Pan05] and by STMicroelectronics [Cof05]. If a commercial silicon laser finally would be available, the sky is the limit and silicon photonics will become reality. It will allow manufacturers to build optical components using the same semiconductor equipment and methods they use now for ordinary integrated circuits, thereby dramatically lowering the cost of photonics.

The presented work fits in this research on silicon opto-electronics. To further lower the cost, the cheapest technology has been selected: standard CMOS, without any optical tricks or flavors. Of course this mainstream CMOS technology has an inherent lower performance than dedicated (Bi)CMOS or compound semiconductor technologies. The goal of this work is to demonstrate the feasibility of light detection in the same CMOS technology that is used to manufacture standard digital circuits. Furthermore, it is shown in theory and practice that the inherent low speed performance of CMOS diodes can be enhanced both on the detector level and on the circuit level. Besides the design of the photodiode, the focus lies on the design of the transimpedance amplifier and the post-amplifier. The main contributions and achievements are:

- The fundamental laws of semiconductor physics have been reviewed to gain in-depth understanding of the opto-electrical mechanisms in silicon detectors. These insights have lead to the development of a one-dimensional
analytical model of the photodiode junction. A complementary numerical two-dimensional model has been developed taking into account more side effects like retrograde doping profiles and side-wall junctions. These effects are important for more complicated diode topologies and will also become more and more pronounced for the emerging nm-scale technologies. Based on this two-dimensional model, the theoretical performances of different kinds of diode topologies have been compared. As the market today is characterized by two important phenomena: Moore’s law on the electrical side and the development of new light sources on the optical side, these trends have been evaluated using the two-dimensional model.

- An in-depth high-level analysis of the shunt-shunt feedback transimpedance amplifier has been presented. Analytical equations have been derived for the transimpedance gain, bandwidth, transimpedance-bandwidth product, loop gain, gain margin and noise. The core amplifier has been modeled as a black box characterized by DC voltage gain $A_0$, input capacitance $C_{\text{in}}$ and output impedances $C_{\text{out}}$ and $R_{\text{out}}$. The applied assumptions and approximations have been pointed out explicitly, as a good designer should be aware that design equations are only valid in a limited design space. However, the trends predicted by these equations form a solid base for a sound design. In a next phase, the amplifier’s black box has been opened, and a literature overview of possible implementations has been given. Finally, a detailed study at the transistor level of three different common-source TIAs has been presented. Confronting simulation results with design equations has revealed that the basic design assumptions are not always valid when pushing the performance to its limits. Also a more accurate noise model for the photodiode has been elaborated, that takes into account the parasitic series resistance.

- The design of a broadband limiting amplifier, consisting of several cascaded gain stages, has been presented. After a (historical) literature study, a Cherry-Hooper topology has been preferred over inductive peaking stages. Analytical design equations have been derived for this broadband stage which again form a solid base for a good design. Also for this building block the assumptions and approximations made to arrive at the equations have been highlighted, so the designer can use them consciously. In addition to the Cherry-Hooper stage, a capacitive source degenerated stage has been analyzed. Finally the technique of offset compensation, indispensable in high-performance LAs, has been disclosed. The theory has been completed with two case studies that clearly illustrate all design choices encountered during the design of an analog high-performance circuit.

- An important achievement reached in this work is the systematic analysis, design and implementation of different CMOS photodiode topologies. The photodiodes have been realized together with TIAs and output buffers in mainstream CMOS technologies and these opto-electronic circuits have been tested in a real-life measurement set-up. Optical signals from a commercial 850 nm transmitter were applied at the input. The
Conclusion is that a differential photodiode is the best topology choice when high bitrates are pursued, at the expense of a lower responsivity. A comparison of the 0.18 µm PDs with the 90 nm PDs, reveals that technology downscaling is not beneficial for the overall photodiode performance. Also for the TIA, newer technologies with higher $f_T$'s are not necessarily better, as it becomes more difficult to achieve a high voltage gain in sub-micron technologies. This high voltage gain is needed to maximize the transimpedance-bandwidth product. This should however not impede the CMOS integration of opto-electrical front-ends in future technologies: analog design engineers will always be inventive enough to find new solutions for new problems.

- To demonstrate the broadband amplifying prospects of CMOS Cherry-Hooper amplifiers, a first LA is designed, manufactured in 0.18 µm CMOS and measured. The experience gained in this design cycle has lead to the design and measurements of a second LA incorporating offset compensation. The performance achieved by this circuit outperforms present state-of-the-art. Table 6.8 compares the described LAs with the LAs studied in Section 5.3. Looking at the CMOS implementations, only [Gal03] (which integrates passive inductors) has a higher gain-bandwidth than [Her06c]. The broadband techniques applied in [Gal03] are undoubtedly very effective to achieve circuits with high gain-bandwidth. However, power dissipation of the core amplifier (excluding output buffers) is higher than in [Her06c].

- The final achievement has also been the largest challenge for the presented research: the realization of a monolithic optical receiver front-end, consisting of a PD, TIA and LA. To realize this goal, a very systematic approach has been chosen, where first the three building blocks have been studied separately, but at the same time their mutual impact never has been neglected. To enhance the speed performance of the differential photodiode even further, an analog equalizer compensates for its frequency roll-off. Table 6.7 compares the presented work with other state-of-the-art integrated opto-electrical receivers and shows that it features the highest level of integration, while its performance is comparable to other designs. The input signals for the photodiode are provided by a commercial available 850 nm optical transmitter. Finally note that, to the author’s knowledge, the chip presented in [Her06c] is the first monolithic CMOS opto-electrical receiver integrating photodiode, transimpedance amplifier and limiting amplifier, that achieves bitrates higher than 1 Gbit/s.
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