Design of an integrated photo detector circuit for laser Doppler blood flow monitoring

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Abstract

A method to measure the blood perfusion of tissue is to apply photons to tissue and measure the frequency shift of the Doppler shifted photons.

To avoid the use of fibers, a chip was designed which contains photodetectors and electronic circuitry to amplify the signal. This IC serves as an interface between the tissue and the signal processor, which transforms the electrical data to medical information about the perfusion of tissue.

To be able to measure at various tissue depths, the die contains photodiodes at various distances from the laser.

To make the photo current less susceptible to noise and disturbances, the current is amplified. The circuit features very low noise electronic circuitry. The electrical input noise current of the circuit is comparable to the noise current of a resistor of 400 kΩ.

The die area is 4.5 by 5 millimeter. The total area for photodiodes is about 0.93 mm². The electronics, which is largely analog, require almost the rest of the available area.

1. Introduction

Laser Doppler blood flowmetry is a noninvasive way to measure the bloodperfusion of human tissue up to a depth of about 1 mm. It is used in plastic surgery and other medical fields.

The principle of laser Doppler blood flowmetry is drawn in figure 1 [1]. A laser transmits photons into the tissue. The photons are scattered and reflected in the tissue. Every photon that meets a moving (blood) particle gets a shift in frequency. A photodiode receives the photons leaving the tissue and converts them into a current. The Doppler shifted photons cause an AC current on top of the DC current from the nonshifted photons. The frequency spectrum of the AC current gives information about the Doppler shift and thus about the bloodperfusion of the tissue.

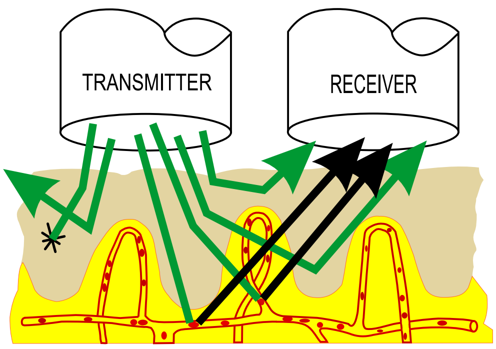

Figure 1. Principle of laser Doppler measurements.

Present laser Doppler blood flowmeters use an optical fiber to transport the photons. A disadvantage of this setup is that movements of the fiber cause a faulty read out.

In this paper, a circuit is described which is to be integrated in a probe for laser Doppler blood flow measurements. The chip contains five pairs of photodiodes at various distances from the laser, analog circuitry to amplify the signal and digital gates to select a source detector distance. Due to the copper cable between the probe and the signal processor, this setup is immune to movements of the cable.

2. System setup

An overview of the system is given in figure 2. The system can be divided in three parts, the photodiodes, the amplifier and the digital circuitry which makes it possible to select another source detector distance. The laser will be mounted on a separate substrate and is not treated here.

The photodiodes are placed in pairs at five distances from the laser. As the DC value of the photocurrent is re-

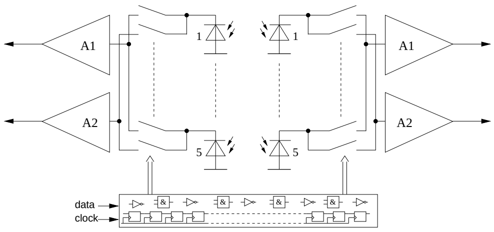

Figure 2. Overview of system.

quired as an output signal, each signal is treated as single ended.

To decrease the influence of disturbances, the signal is amplified by a current amplifier. The probe will be calibrated, so the linearity doesn't have to be high. The AC current contains frequencies up to 40 kHz, which dictates the bandwidth of the system. The most important point of concern is the noise contribution of the system, which has to be as small as possible, the AC signal is rather small and it is easily drowned in the noise.

3. Photodiode

A cross section of a photodiode is given in figure 3. The photodiode has to be made in a CMOS process, so optimization of the photodiode is not really possible.

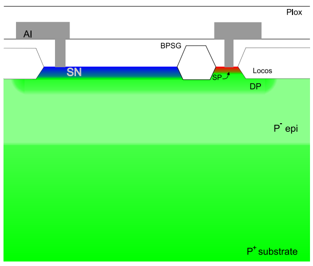

Figure 3. Cross section of the photo diode.

The photocurrent can be written as:

$$I_p = P_{opt} R \tag{1}$$

where I_p is the photocurrent, P_{opt} is the optical power of the light on the photodiode and R is the responsivity of the diode. The responsivity depends on the wavelength of the photons. According to a simulation of the photodiode, the responsivity peaks at a wavelength of 800 nm. In figure 4 the simulated cathode current is plotted against the optical wavelength at a constant optical power (35.68 μW/mm^2). The wavelength of the laser will be 780 nm. The measured sensitivity at a wavelength of 675 nm is 0.3 A/W [2] and 0.32 A/W at 780 nm.

Due to the discrete nature of photons (and electrons) the conversion from light to current produces shot noise. The squared noise current, of the photodiode is given by:

$$\overline{i_n^2} = 2qI_p\Delta f \tag{2}$$

where q is the elementary charge, I_p is the current generated by photons and Δf is the bandwidth. As the AC

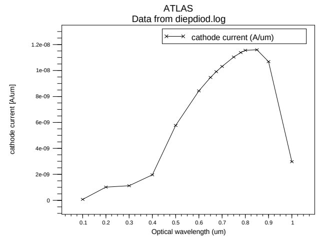

Figure 4. Plot of cathode current of the photodiode against optical wavelength.

current will be small compared to the DC current, the DC value can be used to calculate the noise current.

To increase the signal to noise ratio, the photodiodes at a larger distance from the laser have a larger area. The smallest diode is 100×100 μm and the largest is 1200×100 μm. The diodes are shaped as a part of a ring. (See figure 12 in section 6.)

The graph on the left in figure 5 shows the current of the diode as function of the reverse bias voltage in several cases. The graph on the left shows the result of measurements with a light source as close as possible to a diode (light), with the light source 4 mm above a diode (twilight) and without any light. The graph on the right shows the breakdown behaviour of the diodes. The diodes have a breakdown voltage around 16 V. The high current between 6 and 16 V can be explained by the forward biasing of the pn junction of the PMOS transistors which are used to connect the diode to one of the amplifiers. The bump around 5.4 V could be explained by the presence of a parasitic device.

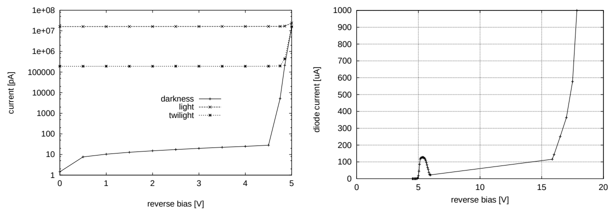

Figure 5. Current of photodiode as function of reverse bias.

4. Setup of Amplifiers

In figure 6 the schematic of the analog current amplifier is given. The photocurrent I is converted into a voltage by transimpedance R1. Then the voltage is amplified and converted into a current again.

The resistors in the circuit have a parasitic capacitance to the bulk. This capacitance reduces the bandwidth of the system. To maximize the bandwidth, the area of the resistor should be as small as possible. The value of the resistor should also be as small as possible but that conflicts with the noise requirement. Neglecting noise in the amplifier, the resistor noise can be modelled as an additional input

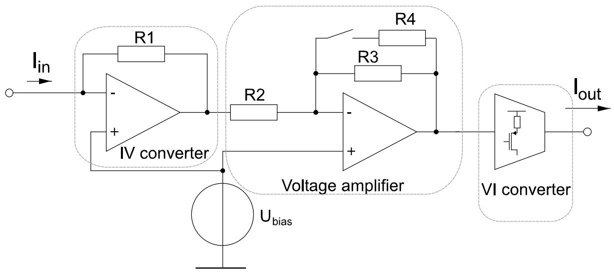

Figure 6. Schematic of the current amplifier.

current source:

$$\overline{i_n^2} = \frac{4kT}{R}\Delta f \tag{3}$$

where i_n is the noise current, k is the Boltzmann constant, T is the absolute temperature, R is the resistance and Δf is the bandwidth. Taking into account a bandwidth of 100 kHz, variations in processing and the amount of noise, a value of 400 kΩ was chosen for the resistor. By dimensioning the other stages in the proper way, the noise performance of the circuit is mainly determined by the first stage.

The opamps in figure 6 are actually common source (CS) amplifiers. The CS amplifier had to be dimensioned in such a way that its noise contribution is small compared to the noise current of the resistor.

The width over length of the amplifying PMOS device of the CS amplifier was set to 2000 micron over 5 micron and its biasing NMOS transistor has a width over length ratio of 600 over 50 micron. The bias current is set to 125 μA.

A disadvantage of the CS amplifier is the low openloop gain. The openloop voltage gain is determined by the g_m of the PMOS transistor of the CS amplifier and the output resistors of both transistors. In formula:

$$A_v = g_m \times (r_{op} // r_{on}) \tag{4}$$

where A_v is the voltage amplification, g_m is the small signal transconductance and r_{op} and r_{on} are the output resistors of the transistors. According to simulations, the g_m is 1.7 mS and the output resistance is 282 kΩ. The resulting voltage amplification is about 480. Loading with 10 kΩ the amplifier reduces it to 31 in the first amplifier and with 250 kΩ to 270 in the voltage amplifier (see below). These values are absolutely sufficient for this application.

The second stage, the block in the middle in figure 6 is an inverting voltage amplifier. Due to the relatively low openloop gain, the amplification will be somewhat lower than R3 divided by R2 (both of figure 6). R4 and the switch make it possible to change the amplification from 24 to 8.

The CS amplifiers are biased by a current reference source. This current source is a V_t-referenced self-biased circuit and can be found in [3].

The output stage is a source follower used as a voltage to current converter (the drain of the PMOS transistor is used as current output). The transconductance is:

$$G_{vic} = g_m + \frac{1}{R} \tag{5}$$

where G_{vic} is the transconductance of the voltage to current converter, g_m is the small signal transconductance of the transistor and R is value of the resistor. The g_m will vary with the DC value of the photocurrent. The effect is reduced by the resistor.

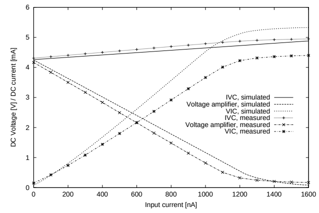

Figure 7. Simulated and measured DC characteristic.

Figure 7 gives the simulated and measured DC characteristic of the amplifier (with the switch to R4 in figure 6 closed). The measured gain is higher for the first two stages and lower at the output of the last stage than the simulation predicted. It can be explained by higher resistor values than expected.

In figure 8 the frequency response of the amplifiers is given. On the left the simulated and on the right the measured. The capacitance of the photodiode is assumed to be 70 pF, which is a worst case value. A smaller capacitance makes the bandwidth a little higher. The measured bandwidth is higher than simulated.

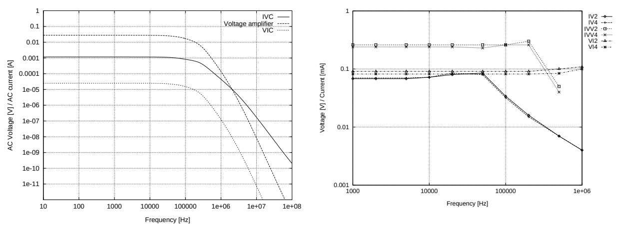

Figure 8. Frequency response of the amplifiers.

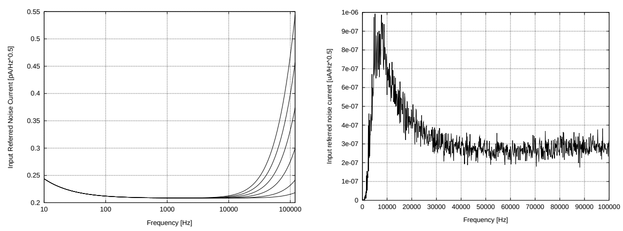

Figure 9. Input referred noise current of the amplifiers.

The input referred noise current of the amplifier for various values of the diode capacitance is shown in the left of figure 9. The diode capacitance was varied from 4.7 pF to 70 pF. The higher the capacitance, the higher the noise at 100 kHz. The temperature is 298 Kelvin. On the right, the measured input referred noise current without any diode connected to the amplifier. The $1/f$ noise is a lot higher than expected due to poor modelling of the noise and because the final H_2-anneal step for reducing interface states in the oxide was not yet done.

5. Digital part

The function of the digital part is to select and connect a photodiode to an amplifier. It consists of switches, see figure 10, some boolean logic in the block 'switch control' and two flip-flops.

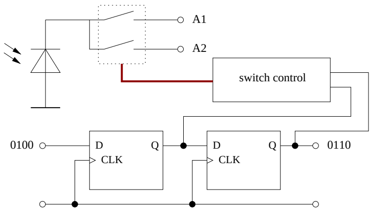

Figure 10. Schematic of photo diode selection principle.

The switches connect the photodiode to one of the amplifiers or to none of them. The switches are actually used as analog switches. As the switches have to pass current instead of a voltage and the voltage at the terminals of the switches remains relatively constant, they can be implemented by PMOS transistors.

The block 'switch control' in figure 10 performs the decoding of the state stored in the flip-flops to control the signals of the actual switches. The decoding is done in such a way that only one switch can be closed at a time. It is possible to connect multiple photodiodes to one amplifier input at the same time. This is not very useful. However additional circuitry to prevent this would require too much area and it does no harm either.

The state of the system, the selected amplifier, is stored in a shiftregister. The user can clock data into the chip to change the state. The shiftregister consists of a chain of flip-flops. The output of the first flip-flop is connected to the input of the second flip-flop and so on. A schematic diagram of a flip-flop is given in figure 11.

During measurements it was discovered that the used flip-flop changes a 0100 data sequence in a 0110 sequence under certain circumstances. So the shiftregister is unreliable. The problem is caused by the delay between the clock signal and its inverse. It can easily be solved in a next realisation.

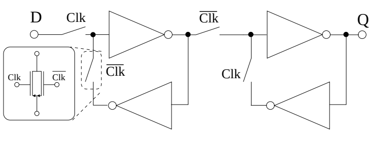

Figure 11. Schematic of a master slave flip-flop.

6. Layout

The chip is 5.0 mm wide and 4.5 mm high. It contains 4 amplifiers, 10 photodiodes, 24 flip-flops and some digital gates, see figure 12. The total area for photodiodes is about 0.93 mm^2. The electronics, which is largely analog, require almost the rest of the available area.

The amplifiers are concentrated in the upper part of the chip, the digital part in the lower/middle part of the chip (it looks like a Σ) and the diodes are the small squares which together form parts of circles.

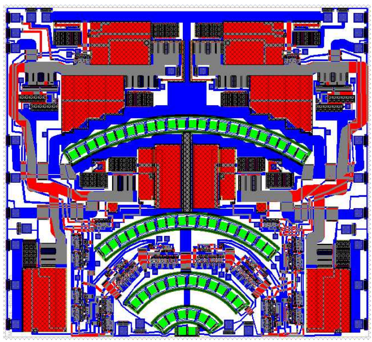

Figure 12. The layout.

7. Conclusion

Simulations and measurements indicate that an integrated photodetector circuit was successfully designed. The simulated performance is excellent for the laser Doppler blood perfusion probe. The circuit has a bandwidth of 100 kHz and a quiescent current consumption of 1.4 mA. The input referred noise current is less than 250 $fA/\sqrt{Hz}$ at a temperature of 298 Kelvin. The circuit makes it possible to measure at two laser diode distances simultaneously. The output current contains both the AC and DC components of the photocurrent. The measured performance is largely as expected. The photodiodes perform well, except for the behaviour above the supply voltage. The amplifiers have a larger bandwidth than expected but also produce more noise. The digital part however needs some redesigning.

8. Acknowledgements

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[1] Perimed, "Principle of laser Doppler measurements," www.perimed.se.

[2] Arthur Kimmels, "Design of an Integrated Photo Detector for a Laser Doppler Blood Flow Monitor," Tech. Rep., University of Twente, Enschede, Feb. 1995.

[3] P. R. Gray and R. G. Meyer, *Analysis and Design of Analog Integrated Circuits*, John Wiley & Sons, Inc., New York, third edition, 1993.