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A reflected-light receiver with 2 nA sensitivity using CDS and separate low-pass filtering of the input signal at each clock-phase

Dirk Killat [a], Richard Schmitz [b]

[a] *Technical University of Darmstadt, Solid State Electronics Laboratory, D-64289 Darmstadt, Germany*

[b] *Telefunken Microelectronic Group, Dialog Semiconductor GmbH, D-73230 Kirchheim, Germany*

Abstract

The design of an integrated receiver for reflected light using correlated double sampling (CDS) is presented. CDS has the disadvantage that input signals of high frequencies are folded back to the base band caused by sampling the continuous input signal. However, the circuit presented here uses a new method to limit the bandwidth of the CDS input signal. Two filter-capacitors, one for each clock phase, are periodically connected to the input of the CDS circuit. As the input signal is low-pass filtered by the ohmic output resistance of the optical sensor in conjuction with the filter-capacitors, aliasing can be avoided. Measurements of a test circuit demonstrate the effectiveness of this principle.

Keywords: Switched-capacitors; Optical sensors; Receivers; Aliasing; Filters

1. Introduction

In optical data-transmission systems (light barriers for monitoring and other similar applications) the carrier-frequency technique is commonly used. The circuits for these systems are realized in the switched-capacitor (SC) technique, e.g., SC filters, modulators and amplifiers. The clock frequency of these SC components has to be much higher than the carrier frequency of the signal, so the advantage of high carrier frequencies is limited.

In our application we use correlated double sampling (CDS) instead of the carrier-frequency technique [1]. Using CDS, the signal is transferred at the baseband and parasitic signals are filtered out if they are not correlated to the clock of the CDS transmission system. This is useful as long as all signals to be handled have frequencies below half of the CDS clock frequency to avoid aliasing [2]. But this requirement cannot be accomplished, because parasitic signals influencing the transmitted signal are not band limited. Hence we have designed a new circuit that low-pass filters the input signal of a CDS amplifier.

The principle of the CDS transmission system is shown in Fig. 1. The light barrier is running with a two-phase clock. In phase one the transmitter is off and the receiver samples the dark input signal plus the background light. In phase two the receiver subtracts the on signal plus the background light from the sampled signal of phase one. Thus the background

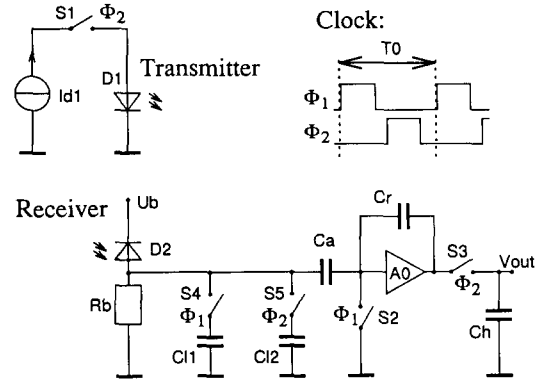

Fig. 1. Principle of CDS using low-pass filtering of the input signal.

light will be eliminated if its frequency is much lower than the clock frequency.

Two switched filter-capacitors, one for each clock phase, represent in conjuction with the ohmic output resistance of the optical sensor an *RC* low-pass filter. If the input signal is constant, each filter-capacitor will sample the corresponding input signal of one clock phase. Hence, the voltages of the two filter-capacitors represent the two input voltages of the CDS amplifier and the CDS principle still works.

2. Theory

The principle of CDS and the spectrum of under-sampled low-pass filtered white noise are discussed by several authors

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[3–5]. Using CDS, we want to eliminate uncorrelated parasitic signals, which in a first approximation can be treated as noise.

Fig. 2(a) shows the signal flow graph of the transmitted signal. The received signal is low-pass filtered by the resistive and capacitive components of the optical sensor (R_b and C_b) as well as by the filter-capacitors C_{l1} and C_{l2}. In our application the capacitance of the photodiode is $C_q = 25$ pF and the load resistance is $R_q = 8$ kΩ. The time constant R_qC_q allows a clock frequency of about $f_0 = 100$ kHz to be used.

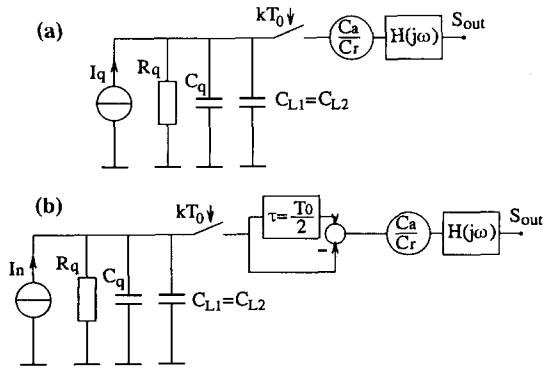

Fig. 2. Signal flow graph for the input signal (a) and the parasitic signal (noise) (b).

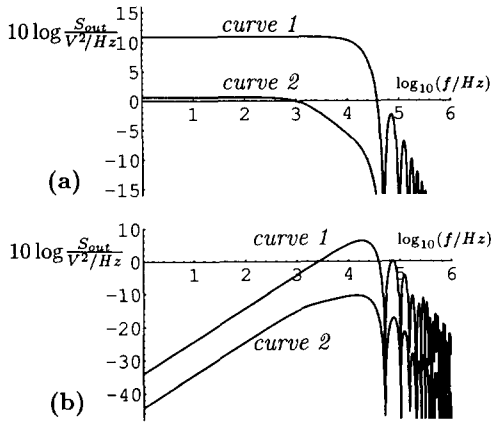

Fig. 3. Calculated spectrum of under sampled noise (a) and CDS spectrum (b).

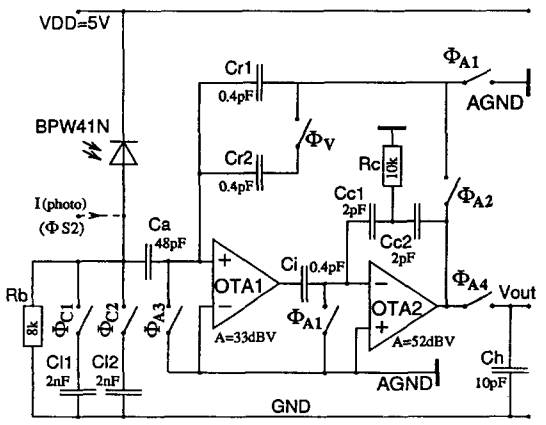

Fig. 4. Schematic of the receiver circuit.

The filter-capacitors $C_{l1} = C_{l2} = 2$ nF low-pass filter the input signal with a corner frequency $f_{c1} = 10$ kHz.

The low-pass filtered parasitic signal, represented by noise, is reduced using CDS as shown in Fig. 2(b). Without the switched filter-capacitors the noise signal has a bandwidth of 800 kHz, thus the noise signal is under sampled and the noise power spectral density S_{out} increases for approximately 10 dB as displayed by curve 1 in Fig. 3(a). If the noise signal is low-pass filtered by C_{l1} and C_{l2}, under sampling is avoided (curve 2 in Fig. 3(a)).

Due to the prevention of under sampling, the CDS principle is improved by approximately 10 dB as displayed in Fig. 3(b). This improvement has to be assessed, because the parasitic signal is not distributed homogeneously. Low-pass filtering is required to avoid foldback of the high-frequency parasitic signal caused by sampling. As a result, CDS combined with a low-pass filtered input signal can be an alternative to the carrier-frequency technique.

3. Design and simulation

We have simulated and designed a receiver circuit. The transmitter and the clock circuit do not involve new methods, so they can be realized as discrete components in an application for testing. Figs. 4-6 show the schematics of the receiver circuit, the operational transconductance amplifiers (OTA1 and OTA2) and the clock diagram. The optical sensor is represented by a BPW41N photodiode with a 8 kΩ resistive load, using a 5 V single power supply. The filter-capacitors C_{l1} and C_{l2} are connected externally. The signal current I_{photo} received consists of a background current component and a signal current and can be injected into the input node in the case of simulation as outlined in Fig. 4. To prevent saturation of OTA1 due to charge injection during the falling

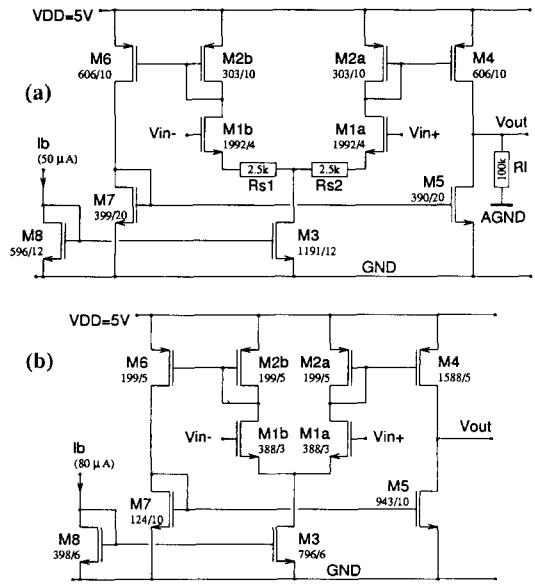

Fig. 5. Schematics of OTA1 (a) and OTA2 (b).

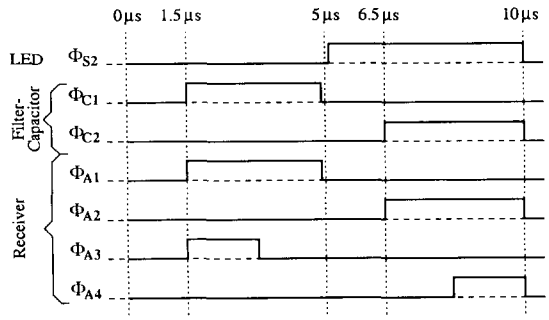

Fig. 6. Clock of transceiver and receiver.

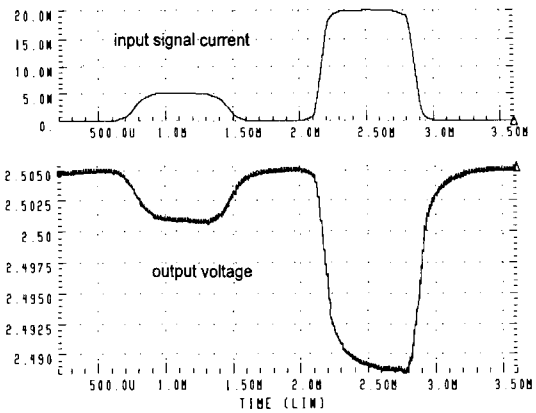

Fig. 7. Transient simulation results.

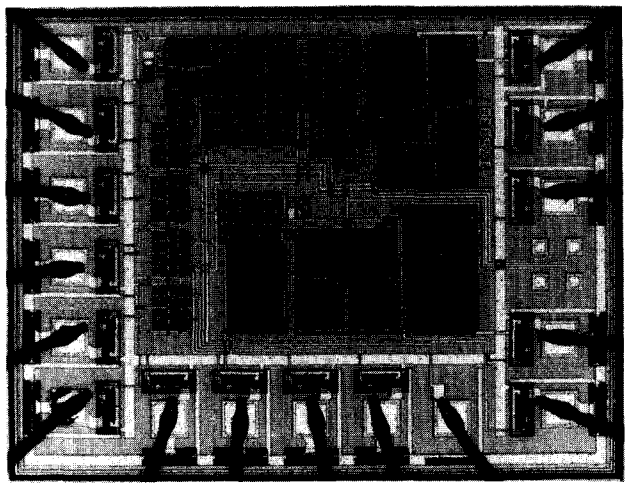

Fig. 8. Microphotograph of the test circuit (size: 1.3 mm × 1.7 mm).

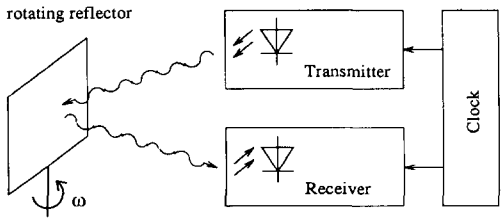

Fig. 9. Measurement set-up with rotating reflector.

edge of clock PA3, OTA1 includes resistive feedback to limit its open-loop gain.

The circuit was simulated with HSpice level 6 models for the MOSFETs. Fig. 7 displays a transient simulation result. The input signal consists of two pulses with amplitudes of 5 and 20 nA and a pulse width of 700 μs. It is obvious that a signal resolution below 5 nA and low-pass filtering of the CDS input signal will be obtained.

4. Experimental results

A test circuit as shown in Fig. 8 was designed in a 1.2 μm double-poly double-metal CMOS technology. The size of the chip is 1730 μm × 1300 μm.

The measurement set-up, shown in Fig. 9, consists of the transceiver, the receiver and a clock. The photocurrent is modulated by a rotating reflector with $f_{mod} = 38$ Hz.

First the transimpedance of the receiver was measured. Fig. 10 depicts the output voltage as a function of time with a $\hat{I} = 100$ nA photocurrent at the input. Hence the transimpedance $Z = 960$ kΩ is in good agreement with the theory.

Secondly the noise performance was examined. Therefore a very low-amplitude photocurrent has to be applied at the input. The rms value of the photocurrent can be calculated from the time function of the output voltage divided by the transimpedance. The time function of the photocurrent shown in Fig. 11 is smoothed with a 225 Hz Hanning filter and yields a value of $i_{photo,rms} = 16.2$ nA.

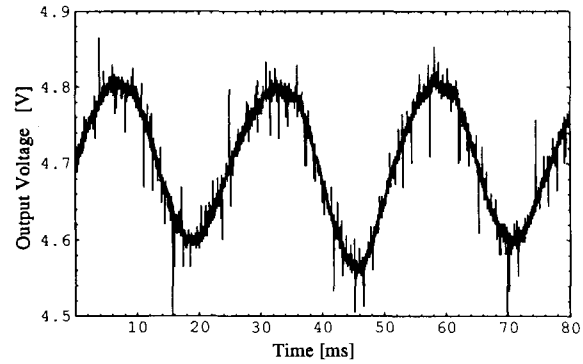

Fig. 10. Output signal with $\hat{I} = 100$ nA signal photocurrent verifying the transimpedance (960 kΩ) of the receiver.

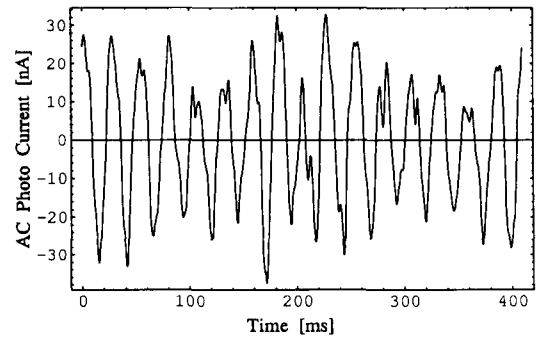

Fig. 11. Output signal with $i_{rms} = 16$ nA signal photocurrent transformed by the 960 kΩ transimpedance to the input.

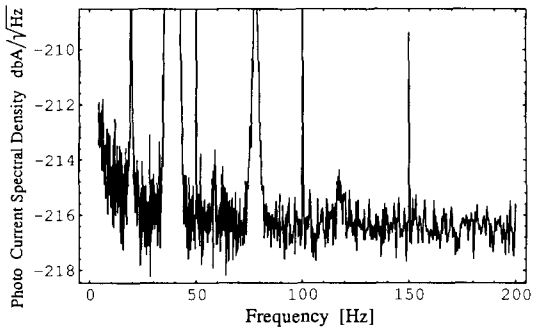

Fig. 12. Output signal spectrum transformed by the transimpedance showing the signal photocurrent spectral density and the 20 pA $(Hz)^{-1/2}$ noise floor.

The frequency spectrum is shown in Fig. 12. It shows the 38 Hz photocurrent with its harmonics and the noise floor. This noise floor is at -214 dBA $(Hz)^{-1/2}$, corresponding to 20 pA $(Hz)^{-1/2}$. As the bandwidth is limited to $f_{el} = 10$ kHz, the equivalent rms input noise current is 2 nA.

5. Conclusions

A new concept for low-pass filtering the input signal of a CDS circuit is presented. This method makes CDS feasible as an alternative for the carrier-frequency technique. So a full-custom ASIC for a reflected-light receiver using this new principle was designed. The filter-capacitors C_{l1} and C_{l2} are connected externally, but a modification of the circuit in future will allow their values to be reduced to make integration possible.

The measurement results are in good agreement with theory and simulation. Photocurrents with an rms value of less than 2 nA can be detected, if their bandwidth does not exceed 10 kHz.

Acknowledgements

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Biographies

Dirk Killat received the Diplom-Ingenieur (M.S.) in electrical engineering from the Technical University of Darmstadt in 1992. He is currently working towards the Ph.D. degree at the Solid State Electronics Laboratory of the Technical University of Darmstadt. His research interest are analog signal processing for sensors, mainly for integrated microtorque sensors.

Richard Schmitz graduated from Fachhochschule Trier and received the Diplom-Ingenieur in electrical engineering in 1983. He is manager of design and test at Dialog Semiconductor GmbH in Kirchheim/Teck. He is responsible for a design group with at present 14 IC-design engineers, developing high-complex mixed-signal ASICs.