A Variable Gain Transimpedance Amplifier Channel with a Timing Discriminator for a Time-of-Flight Laser Radar

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Abstract. **An integrated receiver channel for a pulsed time-of-flight laser rangefinder has been designed. A considerable increase in the input dynamic range of the receiver has been achieved by placing a current buffer with variable attenuation between the external photodetector and the transimpedance preamplifier. The bandwidth of the receiver channel is 170 MHz and the maximum transimpedance 260 kΩ. The distance measurement accuracy is +/- 5 mm, when the signal varies in the range from 1 to 750. The circuit was implemented in a 0.8 µm BiCMOS process.**

1. Introduction

A pulsed time-of-flight laser rangefinder, as shown in Fig. 1, consists of a pulsed laser transmitter, two receiver channels and a time interval measurement unit. A short light pulse, fwhm ~ 5 ns in this case, is sent to a visible target, and the arrival of the reflected pulse is detected. The flight time of the pulse is measured and converted to a distance result. Laser rangefinders are used in industrial measurement applications, such as measuring the profile of hot surfaces in steel factories, the dimensions of large objects in shipyards and the level of flammable fluids in large tanks.

The goal of our work is to develop integrated, low-power electronics for a portable rangefinder using full custom CMOS and/or BiCMOS technologies. We aim at mm-level measurement accuracy and a measurement range of up to 100 m to noncooperative targets. The circuit designed and described here comprises the two receiver channels shown in Fig. 1 and is used to amplify the reference signal from the transmitter and the signal reflected from the target and to produce accurately timed logic level pulses for the time interval measurement unit. A specific aim in this work is to increase the dynamic range of the receiver, which was realized with a current mode gain control block between the photodetector and the preamplifier. The time interval measurement unit has been described in [1].

2. Receiver of the Laser Radar

The receiver channel designed here is shown in Fig. 2. The received laser pulses are detected with a photodiode which converts the optical pulses to current pulses. These current pulses are then converted to voltage pulses and amplified in the transimpedance amplifier channel. The timing discriminator produces accurately timed logic level pulses from the noisy analog input pulses for a time interval measurement circuitry.

The transimpedance amplifier channel consist of a current mode gain control cell (Gilbert cell), a transimpedance preamplifier, a voltage mode gain control cell (R-2R ladder), two cascaded double-stage voltage amplifiers (Cherry-Hooper) and a peak detector. The amplitude of the output pulses of the amplifier channel is measured with the peak detector and the attenuation of the Gilbert cell and the R-2R ladder are controlled accordingly to reduce the dynamics of the signal at the input of the timing discriminator. The timing discriminator consists of a highpass discriminator, a noise comparator and a timing comparator.

To reduce disturbances and the sensitivity to them, the whole receiver channel is differential. Furthermore, the differentiality of the channel improves linearity, which in turn reduces the variation of the delay of the pulses as a function of amplitude. The stability of the propagation delay is of great importance, because it directly affects the measurement accuracy, 7 ps corresponding to 1 mm. Both the start and stop signals travel through identical receiver channels integrated on the same chip in order to reduce delay variation caused by temperature and supply voltage changes and process variations.

The main factors limiting the accuracy of the timing detection are amplitude variation, which, due to nonlinearities and nonideal gain control, may affect the propagation delay of the signal in the amplifier channel and change the timing point in the timing discriminator, as well as noise, which causes random variation of the timing point, see Fig. 3.

2.1. Amplifier Channel

The dynamics of the optical input signal exceeds the dynamic range of the amplifier channel and timing discriminator because of the variation of the target's distance and its reflectivity, and therefore needs to be reduced by means of gain control. This should not, however, lead to any deterioration in the noise properties nor affect the propagation delay or bandwidth. The designed circuit utilises both current and voltage mode gain control to achieve the required dynamic range.

To increase the dynamic range of the whole of the receiver channel the current mode gain control (CMGC) block is placed directly after the photodetector and before the preamplifier and it acts as a current buffer with variable attenuation. This block is the well-known Gilbert quad, as shown in Fig. 4. When the gain is set to maximum by raising vgain, the signal current flows unattenuated through transistors Q1 and Q4. In this case, the cell acts as a common base input buffer and has good noise properties [2]. When vgain is lowered, part of the input current signal flows through transistors Q2 and Q3 to the opposite sides thus resulting in an attenuated output current signal. Lowering the gain increases noise, which can be allowed, however, as lower gains are used only when the signal is strong. The minimum signal is limited by the noise level in the maximum gain mode, whereas the maximum signal is limited by the bias currents of the Gilbert quad.

The addition of the Gilbert cell in front of the preamplifier does not deteriorate the noise properties. The Gilbert quad adds some noise, but at the same time isolates the photodetector and parasitic capacitances from the input node of the transimpedance preamplifier and thus reduces the noise gain peaking at high frequencies [3]. Therefore the total noise remains more or less the same. The smaller input impedance of the common base input helps to improve stability and to achieve a wider bandwidth with the same transimpedance as well as makes the receiver less sensitive to the capacitance of the photodetector and its variations.

The dynamic range of the signal at the output of the preamplifier is wider than the input dynamic range of the timing discriminator, so a voltage mode gain control block, a R-2R ladder attenuator, is placed after the preamplifier.

2.2. Timing Discriminator

The length of the optical pulse used and shown in Fig. 3 is 1.5 m, which is large compared with the aimed mm-level distance measurement accuracy. Consequently, a specific point or constant fraction must be detected accurately and the timing point should be independent of the amplitude of the input pulses. This is achieved here by "differentiating" the input pulses with RC-sections as shown in Fig. 5 and by detecting the crossing of the output signals with a fast comparator. As the passive highpass filters are linear, the shape, and therefore also the crossing point of their output pulses is independent of the signal amplitude. The delay of a comparator is a function of the input signal slew rate and underdrive/overdrive, the delay being shortest with large pulses with fast edges. This delay variation can be partly compensated by arranging smaller signals to cross earlier in the input of the timing comparator. The variation of the timing point as a function of the signal amplitude (walk error) cannot be totally eliminated with this scheme, but the error can be minimized in the applicable operating region, as shown in Fig. 5. With smaller signals, when the compensation is poor, noise prevents the use of the timing discriminator in any case. In this particular case, a highpass corner frequency of 40 MHz was found to give the smallest walk error and best single shot resolution.

A noise comparator is used to enable the timing comparator only when the amplitude of the input pulses is higher than a preset value in order to prevent the noise from causing false detections.

3. Measurement Results

According to preliminary measurements, the bandwidth of the amplifier channel is about 170 MHz, the transimpedance can be controlled in the range from 1.1 kΩ to 260 kΩ and the input-referred noise is ~ 6 pA/√Hz (C_{diode} = 1.6 pF, $C_{parasitics}$ ~ 2 pF, $C_{I/O\ protection}$ = 3.1pF). The variation of the propagation delay of the CMGC block as a function of attenuation is shown in Fig. 6. The delay varies +/- 6 ps (corresponding to +/- 1 mm in distance), when the attenuation is changed from 1 to 1/15. The attenuation of the voltage mode gain control cell (R-2R) can be varied in 3 discrete steps, 1, 1/4 and 1/16, resulting in a delay variation of less than +/- 10 ps. The total gain control range is 1:240.

The walk error of the timing discriminator is shown in Fig. 7. The result varies about +/- 22.5 ps, when the amplitude of its input signal varies from 250 mV to 3 V.

The walk error of the whole receiver channel (taking into account the delay variation of the Gilbert cell, the preamplifier, the R-2R attenuator, the voltage amplifier and the timing discriminator) is less than +/- 5 mm, when the input signal varies in the range from 1 to 750.

The current consumption of the receiver chip during measurement is ~ 50 mA from a single 5 V power supply. The average power consumption can be reduced considerably by switching the channel in power down mode between each measurement (the duty cycle is, for example, ~ 7 % with a pulsing frequency of 100 kHz and measurement range of 100 m). The circuit was fabricated in AMS 0.8 µm BiCMOS process.

4. Discussion

A receiver channel for a pulsed time-of-flight laser radar has been described. The circuit includes all the subblocks needed between the photodetector and the time interval measurement unit. Measurement results show that a mm-level distance measurement accuracy can be realized in a dynamic range of 1:750, which means that in short range applications no additional optical gain control is needed. This simplifies the construction of the laser radar markedly and is a key to an integrated lidar.

References

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2. Vanisri, T., and Toumazou, C.: “Integrated High Frequency Low-Noise Current-Mode Optical Transimpedance Preamplifiers: Theory and Practice”, IEEE Journal of Solid-State Circuits, 1995, Vol. 30, No. 6, pp. 677-685.
3. Graeme J.: “Photodiode Amplifiers: Op Amp Solutions“, McGraw-Hill, New York, United States, 1996.

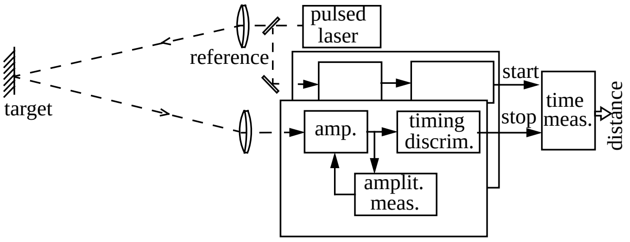

Fig. 1. Pulsed time-of-flight laser rangefinder.

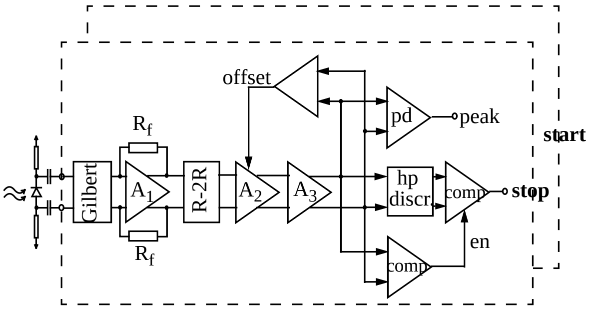

Fig. 2. Designed receiver channel.

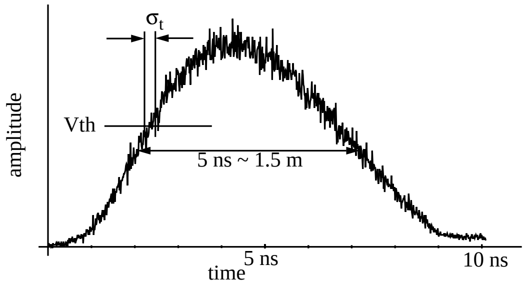

Fig. 3. Laser pulse with noise.

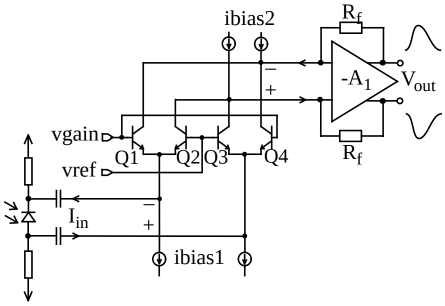

Fig. 4. Current mode gain control in the input.

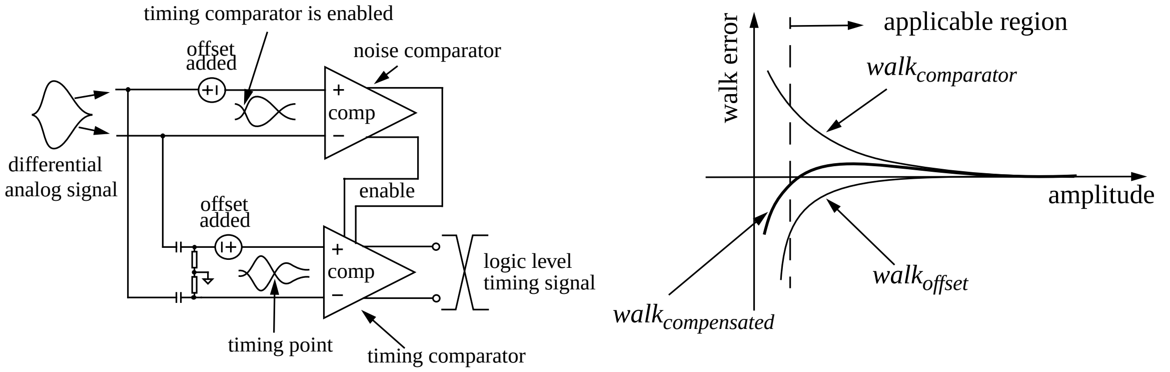

Fig. 5. Differential timing discriminator and walk error compensation.

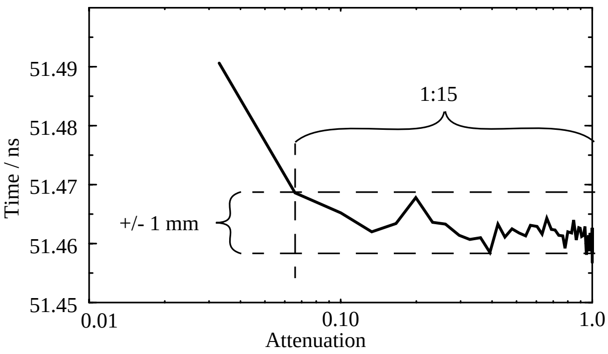

Fig. 6. Delay variation of the input CMGC cell.

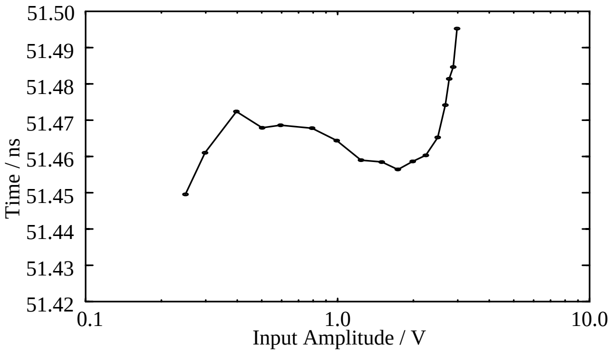

Fig. 7. Walk error of the highpass timing discriminator.