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CMOS receiver for a pulsed TOF laser rangefinder utilizing the time domain walk compensation scheme

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***Abstract* – A receiver channel topology for a pulsed time-of-flight (TOF) laser rangefinder is presented. The designed compact IC receiver chip realized in 0.35 µm CMOS technology will include both a high-performance receiver channel and a time-to-digital converter (TDC). Its timing detection is based on the leading edge detection in the receiver channel. Amplitude-dependent timing error is compensated for by utilizing multi-channel TDC for detecting the pulse width and the slew rate of the received pulse echo and by using this information for calibration. Based on Cadence simulations a timing accuracy of < 100 ps is achieved within a dynamic range of more than 1:100,000.**

I. INTRODUCTION

The pulsed TOF laser ranging method is based on the measurement of a transit time (ΔT) of a short laser pulse (width about 3 ns) to an optically visible target and back to the receiver, as shown in Fig. 1. The measured transit time can be converted to a distance (R) as the speed of light (c) is known

$$R = c \cdot \frac{\Delta T}{2}. \quad (1)$$

A pulsed TOF laser rangefinder typically consists of a semiconductor laser diode transmitter, a receiver channel, an interval measurement unit and a control unit, as shown in Fig. 1.

Optical distance measurement principles can be divided to interferometry, triangulation and time-of-flight [1]. One advantage of all optical distance measurement principles over a microwave radar, for example, is their good lateral resolution owing to the easily collimated laser beam. A LIDAR (light detection and ranging) based on the pulsed TOF is particularly appealing in environmental perception systems where a high measurement speed (>1000 results/s) is needed, where the dynamics of the received echo can be very wide (>1:1000) and where an accurate distance measurement (<1 cm) is needed even with a single transmitted pulse to distances of up to tens of metres to non-cooperative targets. An example of this kind are anti-collision systems and scanners in traffic applications [2],[3] and 3-D

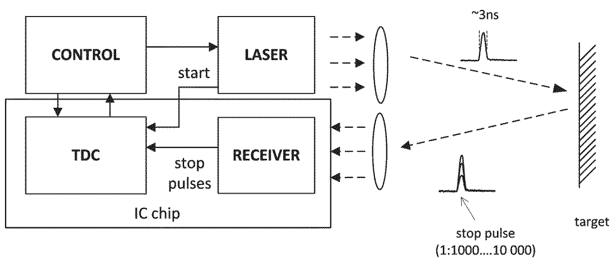

Fig. 1. Block diagram of pulse TOF laser rangefinder.

environmental perception systems [4],[5]. Moreover, the components used in laser radar electronics are typically low-priced and thus this technology is potentially interesting for high-volume applications.

The aim of this work was to develop a novel high-performance integrated laser radar receiver channel topology together with a multi-channel time-to-digital converter (TDC) [6] to be realized on the same IC chip based on the 0.35 µm CMOS technology. With a high level of integration, general purpose and low cost, miniature LIDAR sensor is aimed to serve many future applications in the field of environmental perception.

The main function of the receiver channel of the pulsed TOF rangefinder in Fig. 1 is to generate an accurate logic-level timing signal to TDC. As the accuracy of <1 cm is aimed at, a specific timing point must be discriminated from the detected laser pulse (FWHM ~3 ns corresponds to 50 cm in distance).

In pulsed laser rangefinding systems, a leading edge timing discrimination is the simplest way of detecting received echoes. However, this kind of timing detection suffers from low measurement accuracy in the applications where the dynamics of the receiver echo varies a lot [7]. The generated timing error is usually called walk error and defined as the time walk in the logic-level output signal of the timing comparator produced due to the change in the amplitude of the optical input echo. For example, in automotive applications the dynamic range can be up to 1: 100,000, and as a result the walk error can be in the range of tens of centimetres. Many approaches have been designed to compensate for the dependence of the timing point on the amplitude level of the input signal. In [7] the amplitude, in [8] the slew rate and in [9] the pulse width information

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have been used to compensate for the walk error. Gain control structures have also been used in the receiver channel to keep the signal at a constant amplitude level at the input of the timing comparator [4]. However, gain control circuits often increase the complexity of the receiver system and the achievable dynamic range may still be inadequate.

In this work the designed integrated receiver channel with multi-channel TDC utilizes a walk compensation based on the measurement of both the pulse width [9] and the slew rate [8] of the received input signal. By combining these compensation principles, the benefits of both of them have been utilized as presented in more detail in Section II.

The rest of this paper is organized as follows. The principle of the walk compensation technique is described in Section II. Section III presents the topology of the designed receiver channel. Also the preliminary circuit simulation result are shown in Section III. Finally, the conclusion are given.

II. TIME DOMAIN WALK COMPENSATION

A leading edge timing discrimination principle is used in the receiver channel. The timing comparator gives the timing signal for the TDC as the signal caused by the received optical echo (a pulse with a width of ~3 ns) crosses a constant threshold (V_{th}) at the input of the comparator, as shown in Fig. 2. However, a large timing walk error will be produced since the amplitude of pulse may vary a lot due change in the reflectivity, orientation and the distance of the target, and it should thus be compensated for.

A walk error compensation scheme based on time domain measurements has been utilized successfully in [8] and in [9]. In [8] the walk compensation based on the slew rate (SR) measurement of the received pulse needed two constant thresholds and two comparators to discriminate two timing marks from the rising edge. As shown in [8],[10] when slew rate information is used for walk compensation, the accuracy is improved with a larger difference between the upper and lower threshold voltages. However, a higher threshold ratio will also limit the minimum signal-to-noise ratio and thus the minimum input signal [8], which is an important system level parameter in pulsed TOF laser radar applications.

In [9] we used a walk compensation based on the pulse width measurement. Walk could be accurately compensated for over a dynamic range of more than 1:10 000. We found in [9],[11] that this compensation based on the pulse width measurement also improves the timing jitter particularly at lower SNR levels. This is beneficial especially in scanning applications, where averaging of distance results can necessarily not be made and the single-shot precision is important. However, when the linear range of the receiver channel is exceeded, the pulse width starts to widen rapidly due to charge integration at the input of the receiver. In this region the timing is sensitive to the shape of the trailing edge of the laser

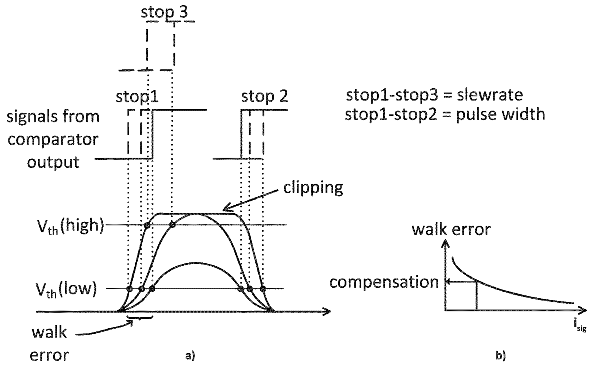

Fig. 2. Walk compensation principle based on pulse width and slew rate measurement.

pulse, which is typically more gentle than the leading edge. The behaviour of the width of the received signal is also more unpredictable and depends on many parameters like input stray capacitance, for example.

In this laser radar receiver, the idea for the walk compensation is to combine these two time-domain compensation principles and their benefits [7],[8]. The operation of the timing discrimination priciple is shown in Fig. 2. It should be noted that in pulsed time-of-flight receiver channels the level of the detected signal must rise above the noise level by a certain margin to keep the false detection rate (due to noise) at a low level. The typical value is signal-to-noise ratio (the pulse amplitude divided by the input referred rms current noise) of 10. The lower threshold voltage (V_{th}(low)) is thus set to the level of about SNR ~ 5. The timing signal stop1 is discriminated from the rising edge of the pulse as the signal crosses the threshold voltage. Stop1 tells the actual distance result including the walk error. The same threshold voltage is also used for the trailing edge of the pulse and the second timing mark (stop2) is generated from that crossing. Another threshold voltage (V_{th}(high)) is used to discriminate the third timing mark (stop3) from the pulse. In order to maximise the variation of the stop1-stop3 interval thus improving measurement accuracy [8], V_{th}(high) is set to the level of SNR ~ 1000.

A multi-channel TDC measures the position of the received pulse (stop1) with respect to the transmitted pulse. It also measures the time differences stop1-stop2 (pulse width) and stop1-stop3 (slew rate) which are then used for walk error compensation. A known relation between the walk and pulse width/slew rate is attained by a separate calibration measurement. As a result, the walk is compensated for in the dynamic range of ~1:100 based on pulse width measurement, which also improves the timing jitter at low SNR levels[9]. After the signal amplitude is high enough to cross V_{th}(high), SR of the received signal can be measured. Within the signal range of ~100:100,000 the known relation between the walk and the slew rate of the signal is used for compensation. Thus the generated walk error through the very wide dynamic range is covered and compensated for and the benefits of both compensation principles are used.

The key issue of accomplishing this kind of walk compensation is the use of a multi-channel TDC of ps level accuracy for the needed time interval measurements [6].

III. THE RECEIVER CHANNEL

A simplified block diagram of the receiver channel is shown in Fig. 3. Fully differential structures have been used at all stages to reduce the effect of disturbances in the receiver channel. The optical echo is converted to a current pulse with an external avalanche photodiode. The current pulse is amplified and converted to a voltage pulse in a transimpedance preamplifier and further amplified in a voltage-type postamplifier. Constant thresholds are used at the input of the timing comparators generating logic-level timing signals for the multi-channel TDC. Threshold V_{th}(low) (SNR ~5-10) is set for the upper timing comparator, and timing marks stop1 and stop2 are received from the output of the this comparator, as shown in Fig. 3. A higher threshold (V_{th}(high)) is used for the other comparator, and the stop3 signal is received from its output. Finally, a multi-channel TDC the operation priciples of which are described in [6], measures distance information (start-stop1), pulse widths (stop1-stop2) and slew rates (stop1-stop3) used for walk compensation. The architecture of the TDC is presented in Fig. 4.

In the case of a mirror-like reflection, a very high input signal may appear at the input of the receiver channel. The input signal can approach 100 mA, which would clearly saturate the receiver channel. For this particular case external Schottky diodes are used to limit the maximum input current to the IC, as shown in Fig. 3.

A. Specifications of the receiver channel

In the environmental perception systems the measurement range can be up to several tens of metres. This means that the optical output power of the laser diode must be high enough (10 to 100 W) so that an adequate minimum signal is received to the input of the receiver from the target. Additionally, the typical minimum width of a commercial laser diode is 3 to 5 nanoseconds at this power level.

The bandwidth of the receiver channel is designed so that the pulse shape is preserved in the receiver channel, meaning that BW~$0.35/t_r$ [12]. Optimizing the bandwidth also minimises the single-shot precision [9]. The bandwidth requirement is about 250 MHz when pulse widths of ~3 ns are used. Based on the previous designs in [7] the input-referred rms current noise can be approximated to about 100 nA with the bandwidth of 250 MHz.

B. Receiver channel simulations

The receiver channel was designed to a 0.35 µm CMOS design process. Cadence Spectre simulations were made for the integrated receiver channel shown in Fig. 3. The simulated transimpedance of the receiver channel was 70 kΩ and 3 dB corner frequency 230 MHz. The input referred current noise was approximated to about 100 nA_{rms}, which was calculated by dividing the simulated voltage rms noise at the input of the timing comparator by transimpedance. SNR (signal-to-noise ratio) of ~10 is needed for reliable distance measurements, and thus the minimum acceptable signal is about 1 µA. The simulation results are presented in Table 1.

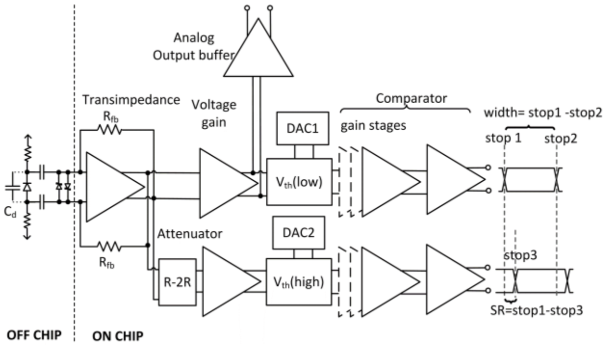

Fig. 3. Block diagram of the receiver channel.

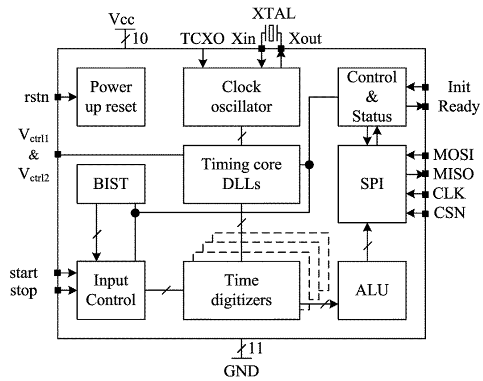

Fig. 4. Block diagram of the TDC.

The walk, pulse width and slew rate simulations were also made to verify the functionality of the combined time domain walk compensation principle presented in Section II. The input current pulse was swept from the minimum input current of 1 µA to 100 mA (dynamic range 1: 100,000). The pulse shape of the digitized laser pulse (FWHM ~3.5 ns), which is used in walk simulations, is shown in Fig. 5. The timing marks stop1, stop2 and stop3 were detected from the output of the timing comparator by using a calculator.

The uncompensated walk error is shown in Fig. 6 as a function of the input amplitude. An uncompensated walk error of 2.5 ns corresponds to 37 cm in distance. The walk error is, however, compensated for using the compensation curves shown in Fig. 7 and Fig. 8.

The compensation curve (black line) in Fig. 7 shows the walk error as a function of the simulated pulse width. In the input current range of 1 µA -70 µA (~linear range of the receiver channel) the depence of the walk and pulse width is also linear. As can be seen within this range, the walk error that should be compensated for is about 2 ns. The dash line tells the level of walk error when the linear range is exceeded (input current ~70 µA) and after that the simulated pulse width starts to widen rapidly.

Fig. 8 shows the walk error as a function of the simulated timing pulse slew rate (black line) in the range of 70 µA - 100 mA. The walk error that should be compensated for in this range is ~600 ps (88 mm in distance), which is also shown in Fig. 7 as a grey line (walk as a function of input amplitude).

To understand the behaviour of a real measurement, an example is given. A receiver detects an input pulse corresponding to input amplitude of 70 µA and generates a logic level timing signal for TDC. The timing signal includes a walk error of 600 ps, as can be seen from the grey line in Fig. 8. However, we would simultaneously measure SR of ~2.9 ns with multi-channel TDC. The compensation curve in the look-up-table tells that SR of ~2.9 ns corresponds to a walk of 600 ps, which is simply subtracted from the position of the received pulse.

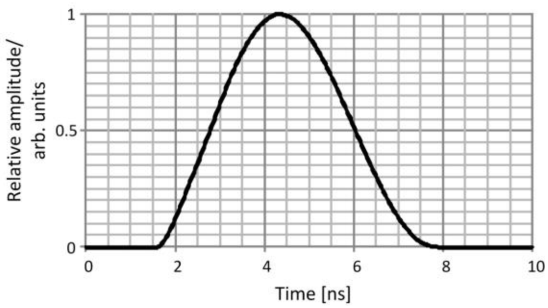

Fig. 5. The pulse shape.

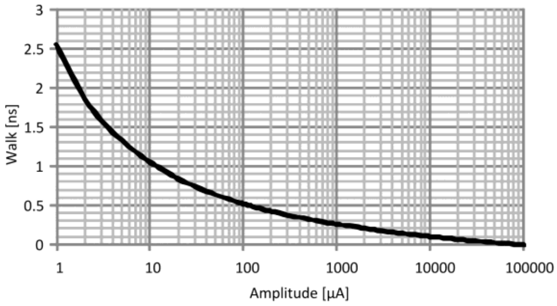

Fig. 6. Walk as a function of input amplitude.

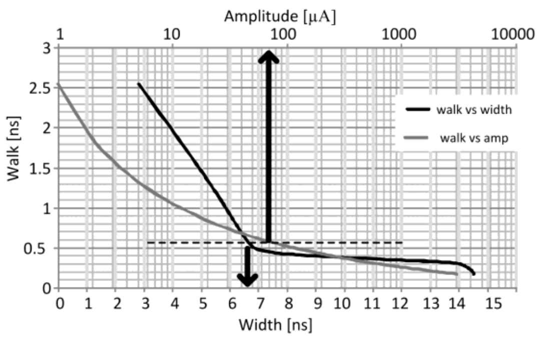

Fig. 7. Compensation curve (walk vs. width).

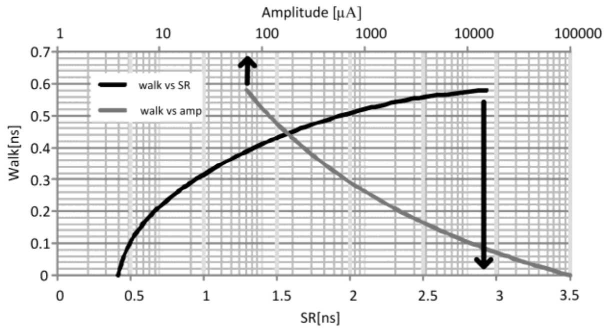

Fig. 8. Compensation curve (walk vs. slew rate).

IV. CONCLUSIONS

A receiver channel for a pulsed TOF laser radar for a variety of future sensor applications is described. A simple leading edge timing detection is used together with walk compensation based on the measurement of the pulse width and the slew rate of the received timing signal and the known relation of these parameters to the walk error. The functionality of the integrated receiver channel is verified by circuit level Cadence simulations. In the final realization the receiver channel and the TDC based on principles given in [6] will be implemented on the same 0.35 µm CMOS chip.

Table 1. Simulation results.

Description	Simulated
Process	0.35 µm CMOS
Bandwidth, -3dB	~ 250 MHz
Input referred current noise (C_{in} =2 pF)	~ 100 nA_{rms}
Transimpedance	~70 kΩ
Uncompensated walk error	2.5 ns

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