Radiation-Tolerant CMOS Timing Readout Circuits for Laser
Detection and Ranging in Nuclear Reactors

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ABSTRACT

A novel multi-stage noise-shaping (MASH) delta-sigma (\(\Delta \Sigma\)) Time-to-Digital
Converter (TDC) structure is proposed for applications in continuous-time pulsed time-of-flight (TOF) rangefinders for nuclear reactor remote sensing, which requires both high resolution and multi MGy gamma-dose radiation tolerance. The converter, implemented in 0.13 \(\mu\)m CMOS, achieves a time resolution of 5.6 ps and an ENOB of 11 bits. The TDC core consumes only 1.7 mW and occupies an area of 0.11 mm\(^2\). Owing to the usage of circuit level radiation hardened-by-design techniques, such as passive RC oscillators and constant-\(g_m\) biasing, the TDC exhibits enhanced radiation tolerance. After a total dose of 3.4 MGy at a high dose rate of 30 kGy/h, the TDC still achieves a time resolution of 10.5 ps. In order to secure the temperature stability of the TDC, a bandgap reference is employed to provide reference current and voltage for the TDC core. The total-ionizing-dose (TID) radiation tolerance of bandgap references in deep-submicron CMOS technology is generally limited by the radiation introduced leakage current in diodes. An analysis of this phenomenon is given in this paper, and a dynamic base leakage compensation (DBLC) technique is proposed to improve the radiation hardness of a bandgap reference built in a standard 0.13 \(\mu\)m CMOS technology. A temperature coefficient of 15 ppm/°C from \(-40°C\) to \(125°C\) is measured before irradiation. The voltage variation from 0 °C to 100 °C is only ±1 mV for an output voltage of 600 mV. Gamma irradiation assessment approves that the bandgap reference is tolerant to a total ionizing dose of at least 4.5 MGy. The output reference voltage exhibits a variation of less than 1 % during the entire experiment, when the chip is irradiated by gamma ray at a dose rate of 27 kGy/h.

1 INTRODUCTION

High resolution timing readout circuits, mainly time-to-digital converters (TDCs), are highly demanded in digital PLLs, ADCs, and time-of-flight (TOF) measurement units, which are widely used for nuclear instrumentation. Demonstrating applications can be found in an accelerator driven system (ADS) like the multi-purpose hybrid research reactor for high-tech applications (MYRRHA): in the spallation target the position of the liquid lead-bismuth free surface needs to be monitored by a laser detection and ranging (LADAR) system. Pulsed LADAR systems are widely used in a variety of remote sensing applications, including marine, space target tracking, and safety control of nuclear reactors. A standard LADAR
system consists of a laser transmitter, two receiver frontend channels and a TDC [1]. The TDC compares the time difference between an emitted laser pulse and the reflected signal. The distance from the LADAR detector to the object can be determined based on the TOF theory. In order to be able to sense a distance difference of 1 mm, a TDC with a time resolution of 6.7 ps is required.

Conventional TDCs were built based on the CMOS gate-delay-line structure, whose resolution is determined by the intrinsic delay of a CMOS inverter gate [2]. As a mainstream integrated circuit fabricating process, commercial CMOS technology has been successfully implemented under ionizing radiation up to 1 MGy, by laying out the NMOS transistors in enclosed geometry [3]. Recent research also shows a trend in advanced CMOS technologies toward increased total dose hardness, due to downscaling of the CMOS gate oxide thickness [4]. This makes modern deep-submicron CMOS technology more suitable for radiation tolerant design. However, for upcoming applications in the International Thermonuclear Experimental Reactor (ITER), electronic components are required to stand for higher than 5 MGy total dose radiation level [5], where the delay of a transistor undergo dramatic changes (on the scale of picoseconds) [6]. In this case, special precautions need to be taken on both system and layout level to secure the circuit's performance. In this work, a radiation tolerant multi-stage noise-shaping (MASH) delta-sigma ($\Delta\Sigma$) TDC is innovated. It adopts the noise-shaping concept, which can improve the effective resolution of a coarse quantizer, but requires no precisely matching analog components.

The remainder of this paper is organized as follows. First, a brief review on pulsed LADAR system and its application in nuclear reactors is given in Section 2. Section 3 explains the proposed MASH $\Delta\Sigma$ TDC in detail. Section 4 introduces the DBLC technique which greatly improves the bandgap reference’s radiation hardness. Section 5 discusses the gamma-radiation assessment results. A conclusion is drawn in Section 6.

2 LASER DETECTION AND RANGING IN NUCLEAR REACTORS

2.1 Architecture of a Pulsed LADAR System

A pulsed LADAR system can detect a distance between the measurement unit and the object according to the time-of-flight theory. A laser pulse is emitted from a laser diode. When it reaches the target, an echo signal is sending back to the LADAR receiver. By comparing the time elapsed between the emission and capture moments, the distance can be calculated as $D = T \cdot C / 2$, where $C$ is the speed of the light.

![Figure 1: Schematic of a pulsed LADAR system](image)

A classic LADAR system is composed by a laser transmitter and an optoelectronic receiver, which normally consists of a photo diode, amplification channel, and a time-to-digital converter (TDC). The spatial resolution of the LADAR system is mainly limited by the
noise in the amplification channel and the time resolution of the TDC. In order to be able to sense a distance difference of 1 mm, a TDC with a time resolution of 6.7 ps is required.

2.2 Implementation of the LADAR System in the MYRRHA Reactor

The MYRRHA reactor, conceived as an accelerator driven system (ADS) which able to operate in sub-critical and critical modes, is currently being constructed at SCK•CEN, Mol, Belgium, as shown in Fig. 2. A liquid metal, for which lead-bismuth eutectic (LBE) has been chosen, is selected as target material to obtain a high neutron gain and to allow forced convective heat removal. In the spallation target, the position of the free liquid metal surface needs to be stabilized in order to guarantee proper heat exchanging and maintaining the spallation process. This can be done by first using a LADAR system to continuously monitoring the liquid metal surface level. The readout of this level serves as a feedback signal to control a pump, which can adjust the position of the LBE surface through a loop.

![Figure 2: Demonstration of the MYRRHA Reactor](image)

3 NOISE-SHAPING TIME-TO-DIGITAL CONVERTER

Previous efforts have successfully implemented a laser driver [7] and a transimpedance amplifier (TIA) [8] in CMOS technology with high radiation tolerance, which could partially form a radiation hardened integrated LADAR system apart from the absence of a high resolution TDC. This work presents a radiation tolerant multi-stage noise-shaping (MASH) delta-sigma (ΔΣ) TDC. It adopts the noise-shaping concept, which can improve the effective resolution of a coarse quantizer, but requires no precisely matching analog components. The MASH TDC employs a low counting clock (55 MHz) to achieve better than 10 ps time resolution, by shaping the quantization noise out from the interested baseband to high frequency.

3.1 First-Order Noise-Shaping TDC

A first-order noise-shaping TDC can be realized by employing the relaxation oscillator, as shown in Fig. 3a. It works as follows: The time signal \( tin \) controls a current to charge one of the two capacitors during its active phase. For instance, \( vinp \) starts rising when \( vinn \) stays at \( vlow \), as illustrated in Fig. 3b. When \( vinp \) exceeds the threshold voltage \( VREF \), the comparator
output becomes ‘1’. This reverses the state of the SR-latch, and triggers the oscillation. The output of the oscillator is connected to a 4-bit counter. The final result in the counter is a digitized copy of the input signal with large quantization error. After the stop signal arrives, the charging current is disconnected from the capacitors. By preserving the residue voltage on the capacitor at the end of each measurement interval, the quantization error $q[k-1]$, which refers to the phase of the oscillator clock, is also preserved. When the following measurement is initiated, the previous quantization error will be subtracted from the next input, since the counter is only driven by the rising edge of the clock. The overall quantization error introduced into this measurement can then be described as

$$q_{err}[k] = q[k] - q[k-1]. \quad (1)$$

3.2 The Third-Order MASH $\Delta\Sigma$ TDC

By cascading more error-feedback structures, a higher order noise-shaping TDC can be formed. In this work, a third-order MASH $\Delta\Sigma$ TDC is demonstrated. The system architecture of a 1-1-1 MASH $\Delta\Sigma$ TDC is shown in Fig. 4. All three stages have the same structure and are followed by a digital processing block. Each stage works as a relaxation oscillator, controlled by the input time signal. The output of the 1-1-1 MASH TDC is given by
\[ D_{\text{out}} = \text{tin} + (1 - z^{-1})^3 \cdot q_{\text{err}3}, \]

where \( q_{\text{err}3} \) is the quantization error in the third stage. All digital blocks used for signal processing are synchronized by the falling edge of the input time signal. The time signal which feeds into a following stage is generated by subtracting the quantization error from the input of the previous stage. This is done by taking the first rising edge of the counting clock as the new start signal, and keeping the same stop signal as the TDC's initial input.

### 3.3 Radiation Hardness Consideration

The on-chip relaxation oscillator provides the counting clock for the \( \Delta \Sigma \) TDC, whose frequency therefore needs to be stable over process and temperature. The period of the relaxation oscillator can be expressed as \( I_{\text{REF}}/(V_{\text{REF}} \cdot 2C) \). By correlating \( V_{\text{REF}} \) and \( I_{\text{REF}} \) as \( V_{\text{REF}} = I_{\text{REF}} \cdot R \), its frequency becomes only dependent on passive components, which is \( 1/(2 \cdot RC) \). Thus, it exhibits inherent PVT variation tolerance. Additionally, in order to obtain robust design against radiation damage, an on-chip radiation-hardened bandgap reference circuit is used to provide \( I_{\text{REF}} \) for each stage and to generate \( V_{\text{REF}} \). The bandgap reference can also improve the TDC’s temperature stability. Radiation hardness of the bandgap reference will be further discussed in section 4.

Due to the fact that the system is operating in a single-ended mode, the demand for matching within one single stage is more relaxed than for a differential system. Moreover, since all noise in a following stage will be suppressed by the total gain of its preceding stages, the inter-stage matching is only important between the first and second stage, and it can be easily improved by using large value capacitances and resistances. On the layout level, guard rings are extensively used for all NMOS and PMOS cells to prevent single event latchup, and also provide better noise isolation.

### 4 Radiation-Hardened Bandgap Reference Using DBLC

Another key technique to insure the radiation tolerance and temperature stability of the TDC besides the noise-shaping, is implementing of a radiation-hardened Bandgap reference. Reference voltage generators are critical building blocks in many analog/mixed-signal systems such as A/D, D/A converters and voltage regulators. In this TDC system, the reference generator provides the threshold voltage for the TDC core. It is required to be stabilized over process, supply voltage, and temperature (PVT) variations. For applications in high-energy physics, space and nuclear reactors, the reference voltage also needs to be stable under high ionizing radiation dose. In order to achieve MGy-level ionizing radiation tolerance, a dynamic base leakage compensation (DBLC) technique is proposed to eliminate the radiation introduced leakage current in the bandgap core.

A bandgap voltage can be generated by summing a CTAT voltage and a PTAT voltage. The CTAT voltage can be directly obtained from the base-emitter voltage of a diode, where the PTAT voltage can be created through the difference between base-emitter voltages of two diodes with different emitter area. In CMOS technology, the two diodes are formed by shortening the base and collector of two \( pnp \) transistors. In n-well CMOS processes, a \( pnp \) transistor can be obtained by doping a \( p^+ \) region inside an n-well which serves as the emitter while the n-well itself serves as base. The p-type substrate acts as the collector and is inevitably connected to the most negative supply.

Although CMOS gate transistors fabricated in deep-sub-micron technology have shown excellent radiation tolerance, the diode still suffers from radiation induced leakage current [9].
A shallow trench isolation field oxide layer is usually placed surrounding the p+ diffusion region, which is the emitter of the pnp transistor. Irradiation induced holes get trapped in the body of the field oxide near the SiO$_2$–Si interface. This will increase the base leakage current, and degrade the current gain of the bipolar transistor. Consequently, when the bipolar transistors are used in a bandgap voltage reference, the output voltage/current will undergo dramatic changes.

![Figure 5: Schematic of a radiation-hardened CMOS bandgap reference](image)

In this work, a dynamic compensation technique is proposed to improve the radiation hardness of the conventional bandgap reference where only normal CMOS diodes are used. The schematic is shown in Fig. 5. The purpose of the dynamic compensation unit is to provide all the base current for the diodes. Therefore, only the collector current is flowing in the core circuits. According to early irradiation assessment results [9], the collector current of the diode is nearly unaffected by the increasing ionizing dose. The base leakage currents induced by irradiation will only flow through the compensation circuits, which keeps the bandgap current $I_{DM5}$ and $I_{DM4}$ remaining unchanged.

The compensation unit works as follows. Resistors R1, R2 and R3 have the same size. OTA1 and OTA2 are used to keep $v_{bl} = v_{br} = v_{bref}$. This is important because $\Delta V_{EQ1,2}$ is equal to $\Delta V_{EBQ1,2}$ only when $V_{BO1}$ equals $V_{BO2}$. Therefore, $I_{R1} = I_{R2} = I_{R3}$. Meanwhile, M1, M2 and M3 have the same size, which gives $I_{DM1} = I_{DM2} = I_{DM3} = I_{R3}$. We also have $I_{R1} = I_{DM1} = I_{DM6} + I_{B1} = I_{DM6} + i_a$. $I_{B1}$ is thus equal to $i_a$. For the same principle, $I_{R2}$ also equals $i_a$. When the base current of the diode increases due to the irradiation induced leakage, it will be compensated dynamically by this base current servo loop. Transistors M8, M9 and amplifiers OTA3, OTA4 are added to further ensure the currents flowing through M1, M2 and M3 are equal.

5 GAMMA-IRRADIATION ASSESSMENT

Radiation assessments have been performed at the Belgian Nuclear Research Centre, SCK•CEN. An on-line dynamic measurement under high dose rate radiation has also been done, proving the TDC’s robustness. The experiment was carried out from the “Brigitte” facility, at a dose rate of 30 kGy/h. Fig. 6 shows the setup of the experiment. The ceramic substrate with the bonded TDC is carried by a container, which is placed in the underwater gamma irradiation facility. The substrate is connected to all measurement equipment by a cable with 10 meters length. The on-line measurement results are shown in Fig. 7. When the system is working in the high conversion rate (50 MHz) mode, the ENOB of the TDC drops only 1 bit after a total dose of 3.4 MGy. This means that a resolution of 10.5 ps can still be achieved. The TDC works functionally till at least 5 MGy. The current consumption of the TDC system is nearly unaffected during the whole irradiation period.
The effectiveness of the DBLC technique has also been evaluated by a real-time gamma radiation assessment. The experiment was carried out from the “Brigitte” facility. Substrates bonded with both conventional bandgap references and radiation-hardened bandgap references from the same technology run are irradiated with $^{60}$Co gamma source. A high dose rate of 27 kGy/h is obtained, which enables us to achieve a TID of 4.5 MGy in one week.

As shown in Fig. 8, the output reference voltage of the bandgap employing the DBLC technique stays consistently with the pre-rad value. A variation of only 1% is found from 0 to 4.5 MGy. At the same time, the output voltage of the conventional bandgap reference
increases more than 15% during irradiation. After the irradiation stopped, the output voltage of the DBLC bandgap reference can be easily recovered to the pre-rad value by self-annealing.

6 CONCLUSION

This work addresses several practical issues regarding the application of timing readout circuits in harsh environments. In order to obtain precise timing measurement in a nuclear reactor where electronic components suffering from high total ionizing dose, we proposed a novel noise-shaping TDC structure. Gamma radiation assessments with a high dose rate of 30 kGy/h have been performed, proving the TDC's radiation hardness. After an extremely high radiation dose of 3.4 MGy, a 10.5 ps time resolution is still achieved. The temperature stability of the TDC system is secured by employing a radiation-hardened CMOS bandgap voltage reference. The output voltage of the DBLC bandgap has shown a variation of only 1% after 4.5 MGy total dose gamma irradiation at a dose rate of 27 kGy/h.

REFERENCES


