A LOW POWER HIGH ACCURACY CMOS TIME-TO-DIGITAL CONVERTER

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ABSTRACT

In this paper, we present a new CMOS time-to-digital converter (TDC) with the cyclic delay line structure. The static supply current is 2-nA only. Furthermore, the continuous calibration is no longer needed. The TDC can be shunt down between measurements to make the power consumption negligible. The circuit with 64-stage cyclic delay line has been fitted into $0.25\text{mm} \times 0.75\text{mm}$ chip area with a typical $0.8\text{-}\mu\text{m}$ SPDM process. The measured resolution is 286 picoseconds, and the measured single-shot accuracy is less than 143 picoseconds. Both can be made much less if the control voltage is well tuned.

1. INTRODUCTION

Time interval digitization is an important building block for many instrumentation circuits, such as range finder, phase meter, robot vision, PM demodulator, etc.[1-3] Due to its large power consumption and circuit size, the conventional TDC with subnanosecond resolution can hardly be implemented in the portable systems[4]. At the end of 1995, a novel TDC circuit, named linear TDC here due to its linear delay line structure, is proposed to get 780 picoseconds resolution (after averaging hundreds of measurements) with 15 mW power consumption[5]. The portability problem is thus solved at the expense of 3ns single shot accuracy. Figs. 1a and 1b show the block diagrams of the circuit and the pulse-shrinking delay element.

Basically, the pulse-shrinking delay element is a signal buffer composed by two NOT gates. The maximum conductible current of the first NOT gate is controlled by the bias voltage V_{bias} . The degree of width shrinking of the input pulse can be easily controlled through adjusting V_{bias} . A reference pulse with duration T_{ref} is fed into the delay line for calibration. The delay-locked loop, cooperating with another delay line of same size, will adjust V_{bias} to make the reference period disappear ex-

actly in the last delay element. In the measurement, the input period T_{in} with $T_{\text{in}} \leq T_{\text{ref}}$ will be fed into the delay line instead. Suppose that T_{in} disappears in the n -th delay element, then the width is measured as $n \times T_{\text{ref}} / N$, where N is the number of elements in the delay line. For a 20 MHz reference clock and a delay line of 64 elements, the resolution is $50\text{ ns}/64=780\text{ ps}$ theoretically.

(a)

(b)

Fig. 1a The block diagram of the linear TDC
1b The pulse-shrinking delay element

This circuit established a milestone of low-cost, high-accuracy portable TDC systems. But there are still some important features needed to be improved. Due to many unavoidable variations [5,6], the calibration of the TDC must be done continuously to keep T_{ref} just disappear in the last element of the delay line. This consumes much system power, and the circuit can not be shunt down between measurements for power savings. Also,

the mismatch among pulse-shrinking delay elements results in poor delay line linearity. This sets a serious limit to the TDC resolution. When higher TDC resolutions are required, the pulse-shrinking delay line must be lengthened to accommodate more delay stages. And the linear TDC will become too long and must be folded into 2 or more segments due to reasonable chip width or length limit. The inter-segment wiring is much longer than the intra-segment one[6]. It causes large non-linearity error and further limits the resolution of the TDC to be 6- to 7-bits only.

Finally, the input pulse shrink more rapidly at the last few elements, because it will become too short to drive the next stage to toggle its state. For the TDCs with coarse resolution, this phenomenon may not be noticeable. But for the TDCs with deep sub-nanosecond resolution, this kind of nonlinearity will dominate and deteriorate the accuracy. To overcome all these problems, a new TDC circuit is proposed in this paper. The circuit has been implemented by a 0.8- μm SPDM CMOS process.

2. OPERATION PRINCIPLES

The block diagram of the new TDC is shown in Fig. 2a. The input pulse circulates in the cyclic structure. It shrinks a certain amount in each cycle until it thoroughly diminished. Assume that the counter counts N for the reference input T_{ref} and n for the test interval T_{in} , then T_{in} is measured as:

$$T_{in} = \frac{n}{N} T_{ref} \quad (1)$$

Fig. 2a The conceptual block diagram of the new TDC
2b The circuit of the new TDC in Fig. 2a

Practically, the pulse-shrinking delay elements can also served as delay units. So, the ideal delay line in Fig. 2a is replaced by series-connected pulse-shrinking delay

elements as shown in Fig. 2b. Since the whole circuit of the new TDC is equivalently composed by even number of NOT gates, there are two stable states, $V_0=V_1=\dots=V_{out}= \text{LOW}$ and $V_0=V_1=\dots=V_{out}= \text{HIGH}$. Where V_i is the output of the i -th element in the delay line. To make sure that the circuit settles in the proper stable state $V_0=V_1=\dots=V_{out}= \text{LOW}$ from power on, an external control pin RESET must be added as shown in Fig. 2b. The degree of shrinking is controlled by the bias voltage V_{bias} which can be adjusted to get over 10^2 or much more cycles for the reference period T_{ref} . The corresponding resolution can be extremely fine.

Because the element mismatch and intra-segment wiring mismatch discussed will be went through per cycle by the input pulse, there will not be any measurement nonlinearity from cycle to cycle. The linearity problem is solved successfully. In this new TDC, it is not necessary to keep the reference pulse T_{ref} just disappeared at some specific cycle or stage. Only if the bias voltage V_{bias} is properly adjusted such that T_{ref} circulates the delay line enough times before diminished out to keep sufficient resolution. The continuous calibration is no longer needed, and the circuit can be shunt down between measurements to save power. Also, the associate delay-locked loop and its cooperating delay line can be saved. This greatly simplifies the TDC circuit.

Basically, the output bits of the new TDC are unlimited. It can be increased by merely adding the number bits of the internal counter in Fig. 2b. And the control of V_{bias} must be made accurate enough. On the contrast, the linear TDC[10] must double the size of its delay lines to increase merely one output bit. No averaging is needed to improve the resolution. Because the single-shot resolution itself is accurate enough. The nonlinearity, caused by the pulse shrinking out more rapidly at the last few stages, can be treated as a constant count offset for a given bias voltage V_{bias} . And it can be completely calibrated out by the following technique.

Offset Elimination: First, feed T_{ref} and $T_{ref}/2$ into the TDC input. Assume that the circuit gets N and N' counts respectively. Then

$$T_{ref} = \alpha N + T_{offset} \quad (2)$$

and

$$\frac{T_{ref}}{2} = \alpha N' + T_{offset} \quad (3)$$

Where α is the effective resolution, and T_{offset} is the measurement offset caused by faster shrinking just before the input pulse disappeared.

$$\alpha = \frac{T_{ref}}{2(N - N')} \quad (4)$$

$$T_{offset} = \frac{T_{ref}(N - 2N')}{2(N - N')} \quad (5)$$

If the calculated resolution α is above requirement, we must raise V_{bias} carefully to make N large enough. This in turn lowers the effective resolution α to a satisfactory value as expected from eq. (4). Next, feed measured interval T_m into the TDC input, and assume that the counter result is n . Then, the measured width of T_m becomes:

$$T_m = \alpha \times n + T_{offset} = \frac{T_{ref}(n + N - 2N')}{2(N - N')} \quad (6)$$

3. EXPERIMENTAL RESULTS

To demonstrate the feasibility of the proposed TDC, we have fabricated the circuit with a 0.8- μm SPDM CMOS process. The new TDC is composed by 64 delay elements with $(W/L)=3\mu\text{m}/0.8\mu\text{m}$ for P1 and N1 transistors, $(W/L)=7.6\mu\text{m}/0.8\mu\text{m}$ for P2 transistor, $(W/L)=2.3\mu\text{m}/0.8\mu\text{m}$ for N2 transistor, and $(W/L)=1.3\mu\text{m}/0.8\mu\text{m}$ for N3 transistor in each pulse shrinking delay element. The photomicrograph of the new TDC is shown in Fig. 3. The size of circuit is reduced to 0.14 mm $\times$ 0.75 mm (without the internal counter). If the internal counter is included also, the chip size is estimated to be 0.25mm $\times$ 0.75 mm. All the experimental results presented here are collected from these prototype chips. The static dissipation current is less than 2 nA, and the average current consumption is calculated to be less than 100 nA from a 5-V supply.

Fig. 3 The photomicrograph of the new TDC

Fig. 4a shows a typical output code distribution for 50 single-shot measurements of the new TDC. Compared with Fig. 4b, the typical distribution of single-shot measurements of the linear TDC[5], the single-shot measurement of the new TDC is very stable. No averaging is needed to improve the resolution. To explore the

effective resolution and the measurement offset of the new TDC, a series of experiments with the same condition were conducted. The only parameter varied was the width of the input pulses generated by HP 8110A pulse generator. The same input pulse widths were also measured with a Stanford Research Systems SR620 universal counter. The measured results of single-shots along with the theoretical prediction line are depicted in Fig. 5a. It shows that the experimental data agrees with the prediction. From eq. (2), the effective resolution α is calculated to be 286 ps. Also, the measurement offset T_{offset} is calculated to be 344 ps. This again confirms our inference that the input pulses shrink faster just before diminished. The dead time of single-shot measurements is at most a few microseconds. The measurement rate of at least 100kHz is promised. Fig. 5b shows the error between single-shot measurements and the theoretical calculation. All the errors are below 1/2 resolution (143 ps). This assures every output bit is valid.

Fig. 4 Typical distribution of single-shot measurement results in 50 measurements for (a) the new TDC, (b) the linear TDC

The effective resolution and the single-shot accuracy can be further improved, if we control the bias voltage V_{bias} more accurately. By simulations, the resolution of the new TDC can be as low as tens of picoseconds or less. Table I shows a portion of simulation result for $V_{bias} = 3.10V$ and $T_m = 6.0ns$. The effective resolution is about 37.5 ps.

Fig. 5a The result of the single-shot measurements and the theoretical prediction line
5b The measured single-shot error

Table. I The beginning portion of the simulation result with $V_{bias}=3.10V$, $T_{in}=6 ns$.

pulse no.	1	2	3	4	5
width(ns)	5.9758	5.9384	5.9008	5.8633	5.8258
shrinkage(ps)		37.4	37.6	37.5	37.5
	6	7	8	9	10
	5.7884	5.7509	5.7135	5.6759	5.6385
	37.4	37.5	37.4	37.6	37.4

4. SUMMERY

An extremely low-power and high-accuracy CMOS time-to-digital converter with the cyclic delay line structure has been presented. With the $0.8\text{-}\mu\text{m}$ SPDM process and 64 delay elements, this new TDC can measure input interval up to $20 ns$ and reach a resolution of $286 ps$ experimentally. The measured single-shot accuracy is less than $1/2$ resolution. No averaging is needed to improve accuracy. The TDC induces almost no extra cost for increasing the number of its output bits. When cooperated with TDCs using counter method, this TDCs can be used as interpolation circuits[7] to greatly increase the linear measurement range while keeping the same resolution. No continuous calibration is needed. This enables the TDC to be shunt down between measurements to save more battery power. This certainly opens another possible applications of the new TDC in low power and portable systems.

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