Programmable pulsewidth control loop (PWCL) in dual-slope combination

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Abstract: A new technique to adjust the duty cycle of the output clock by adopting a pulsewidth control loop (PWCL) in dual-slope combination is presented. Correcting both rising and falling slopes simultaneously in their combination leads to a simple way for a wide correction range. Furthermore, the duty cycle can be easily adjusted to a desired value by setting up the programmable current sources in the charge pump. A generic circuit is suggested, and its validity is verified in a 0.13- μm CMOS technology under 1.2 V supply. The simulated results with Spectre exhibit the integral nonlinearity (INL) of less than 2% for the output duty-cycle range from 6.25% to 93.75% with the consideration of process, voltage, and temperature (PVT) variation.

Keywords: duty cycle, pulsewidth control loop (PWCL), programmable

Classification: Integrated circuits

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1 Introduction

The systems adopting half-rate techniques require a clock with 50% duty cycle. Unfortunately, the process, voltage, and temperature (PVT) variations may cause its deviation from the desired value. Several pulsewidth control

loops (PWCL) to tolerate the PVT variations [1, 2, 3] have been presented. However, the unbalanced variation between two charge pumps may create large jitter [1, 3], or an additional overhead of the hardware and power consumption is encountered [2]. Above all things, these works hardly provide any prescribed strategy of adjusting the duty rate. A programmable PWCL utilizing a voltage-controlled delay line (VCDL) in a 3-state sequential circuit to determine the falling edge of the output clock [4] was reported. It overcomes many drawbacks of the previous works, but the delayed version of the reference clock propagating through the VCDL and flip-flops for correcting the duration still restricts the adjusting range of the duty cycle.

In this paper, a new topology of pulsewidth control loop (PWCL) in a dual-slope combination is proposed without using any variable delay lines as in the prior works [1, 2, 3, 4]. Controlling both rising and falling slopes with an efficient combiner provides some fundamental strategies to make any duration rate possible. A typical implementation of the topology is suggested and its performance results are described.

2 Concept of correcting duty cycle

Fig. 1 (a) represents a block diagram of the proposed PWCL to take in the wide duty-cycle range of the input (CK_I). It consists of a slope modifier, a pulse combiner, and a charge pump. The duty cycle of CK_O and $\neg CK_O$ is converted to the tuning-line analog voltage, v_c , which is then fed back to the slope modifier. The duty-cycle information on the current complementary outputs is represented by v_c which is updated every iteration, and finally settles down. The variation of circuit parameters such as gate propagation delay, logic threshold voltage, and device drivability would be alleviated through the loop operations, resulting in little long-term effects.

Recognizing that the input and output quantities, Φ_I and Φ_O , are the excess phases from the ideal position, a linear model to describe the duty-cycle correcting dynamics is shown in Fig. 1 (b). In this case, $K_{VC\Phi}$ represents the gain of the correction associated with the slope modifier and the pulse combiner. It would be considered to be a function of the trans-conductance of the current source and the output capacitance in the slope modifier shown in Fig. 1 (c). I_B and C are the bias current and the storage capacitance of the charge pump, respectively. The closed-loop gain for the excess phase can be expressed such as

$$\frac{\Phi_O}{\Phi_I}(s) = \frac{2\pi C s}{2\pi C s + K_{VC\Phi} \cdot I_B} \quad (1)$$

where a dc zero and a left-half plane pole are involved. Therefore, the dynamic correction range and the gain of the in-band correction can be expressed in (2) and (3), respectively.

$$\omega_0 = \frac{K_{VC\Phi} \cdot I_B}{2\pi C} \quad (2)$$

$$G \cong \frac{2\pi C \omega}{K_{VC\Phi} \cdot I_B} \quad (3)$$

Fig. 1. Proposed PWCL: (a) block diagram (b) linear model (c) concept of slope modification and composition.

A conceptual diagram for the slope modification followed by a pulse combiner is illustrated with its conceptual operations in Fig. 1 (c). Falling-slope (CK_{HD}) and rising-slope (CK_{LD}) modifiers are placed in parallel, each consisting of complementary switches driven by the input clock, a current source (I_{LD} or I_{HD}) controlled by the analog tuning-line voltage, v_c , and a capacitor. The pulse combiner driven by both CK_{HD} and CK_{LD} composes a composite pulse, and then produces the corresponding complementary clocks, CK_O and $/CK_O$.

The basic operation, when the switch resistance is neglected, is as follows. The tuning-line voltage, v_c , affects the output slopes of the modifier in the opposite direction since it is applied to the opposite types of current sources. If v_c decreases, so I_{HD} decreases and I_{LD} increases, the falling slope of CK_{HD} becomes slower while the rising slope of CK_{LD} becomes faster, and vice versa. The correction mechanisms in the three appreciable cases are suggested when the duty cycle of the input CK_I is under 50%, over 50%, or near 50%. Under 50%, the time required for CK_{LD} from Gnd to reach the logic threshold

voltage (V_{logic}) of the following pulse combiner determines the falling instance of CK_O , expanding the pulse duration. For over 50%, the time for CK_{HD} from V_{DD} to V_{logic} determines the rising instance of CK_O , reducing the pulse duration. Near 50%, the duration is nearly maintained since both edges are moving in the same direction. In all cases, the composition of the edges forms a modified duration depending on the tuning-line voltage, v_c . The duty-cycle correction should be completed by forming a PWCL, as shown in the block diagram of Fig. 1 (a).

3 Circuit design and simulation results

Fig. 2 (a) depicts a CMOS realization of the open-loop path from CK_I to CK_O and $/CK_O$. The slope modifier consists of current sources, M_1 and M_6 , and complementary switches M_2 , M_3 , and M_4 , M_5 , for CK_{HD} and CK_{LD} , respectively. The pulse combiner consists of four stacked transistors, $M_7 \sim M_{10}$ followed by a latch. The complementary CK_O and $/CK_O$ are generated via the balanced inverter chains. The rising edge of CK_{HD} which always advances that of CK_{LD} enables the pull-down path (M_8) while disabling the pull-up path (M_{10}). The rising slope of CK_{LD} , then, turns on M_7 , beginning to draw current through M_{12} . Eventually, the logic threshold encountered by the rising slope of CK_{LD} is determined by M_7 , M_8 and M_{12} .

Similarly, the falling edge of CK_{LD} and the falling slope of CK_{HD} enable the pull-up path through M_9 and M_{10} in this order. Again, the logic threshold encountered by the falling slope of CK_{HD} is determined by M_9 , M_{10} and M_{11} . The latch acts to hold the previous value during the instantaneous high-impedance interval from the leading edge to the late slope.

The duty cycle of the output can be adjusted by configuring the binary-weighted current sources in the charge pump, as illustrated in Fig. 2 (b). The tuning-line voltage, v_c , settles down when the incoming pull-up charge is equal to the outgoing pull-down charge. That is, in the steady state

$$I_{B1} \cdot T_{/CKO} = I_{B2} \cdot T_{CKO}, \quad (4)$$

where $T_{/CKO}$ and T_{CKO} are the “high” durations of $/CK_O$ and CK_O , respectively. If the expression of (4) is substituted into the following definition, the duty cycle could be ultimately controlled with respect to the ratio of I_{B1} to I_{BT} .

$$duty\ cycle = \frac{T_{CKO}}{T_{CKO} + T_{/CKO}} = \frac{1}{1 + \frac{T_{/CKO}}{T_{CKO}}} = \frac{1}{1 + \frac{I_{B2}}{I_{B1}}} = \frac{I_{B1}}{I_{BT}} \quad (5)$$

Typically, the current segments of I_{B1} will be allowed to be the same as those of I_{B2} , except for the extra termination current source I_u . The digital codes from D_1 to D_8 control the segments of both I_{B1} and I_{B2} , pertaining to maintain the total current, I_{BT} , constant.

In order to prove the validity of the proposed PWCL, a full transistor-level circuit in a 0.13- μ m CMOS process under 1.2 V supply voltage was designed. The Spectre simulation results in Fig. 2 (c) exhibit INL error versus digital

(a)

(b)

(c)

Fig. 2. Circuit diagrams of (a) slope modifier and pulse combiner, (b) programmable charge pump, and (c) Spectre simulated results with input duty cycle of 20% and 80%, respectively.

code with PVT variations when the applied input is at 100 MHz with the duty cycle of 20% and 80%, respectively. The INL error is observed to increase as the code gets out of the center point of 50% duty cycle (digital code = 0111). It is primarily due to the finite output impedance of the source device, leading to the mismatch between the pull-up and pull-down currents as the code varies. Table I summarizes the comparison results between the proposed and the conventional PWCLs.

Table I. Performance comparison with prior works.

	This work	[4]
Technology	0.13- μ m CMOS	0.35- μ m CMOS
Supply Voltage	1.2V	3.3V
Control Stage Type	Slope modifier	Tri-state control
Operating Frequency Range	~ 1 GHz	1 GHz ~ 1.27 GHz
Input Duty Cycle Range	20% $\sim$ 80%	–
Output Duty Cycle Range	6.25% $\sim$ 93.75%	35% $\sim$ 70%
Active Die Area	0.25 x 0.17 mm ²	0.47 x 0.3 mm ²
Power Consumption	16 mW	150 mW

4 Conclusion

A duty-cycle control circuit with small area is developed by adopting a pulsewidth control loop (PWCL) without variable-delay lines. The simultaneous modification of both rising and falling edges of the input in their combination leads to the precise correction over the wide covering range of the input duty cycle. In addition, to achieve a wide programmable range of the output duty cycle, a charge pump with programmable current sources is used. The analysis with a linear model was suggested to investigate the loop dynamics. The proposed PWCL system was designed in a 0.13- μ m CMOS technology. System parameters and performance results from Spectre simulations are described.

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