Implementation of a Ramp Generator with Schmitt Trigger Circuit for PWM Modulator Applications

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Abstract— A ramp (sawtooth wave) generator consisting of the voltage-current converter circuit, PMOS two-stage operational amplifier, current mirror and Schmitt trigger circuit is presented for the application of PWM modulator in this paper. The PWM modulator is one the PWM control core circuit of the switching power converters or the supply modulator of a wideband wireless transmitter. This paper proposes a ramp generator with Schmitt trigger circuit replace the conventional ramp circuit by use of two hysteresis comparators and one S-R latch circuit. The ramp generator with Schmitt trigger circuit can application to low power management integrated circuits, not only can reduce the area of the chip, more able to reduce the power consumption of the chip. This proposed ramp generator for PWM modulator circuit is design and implemented using the TSMC 0.35 μm 2P4M process technology. Based on measured results, the chip size is $671.99 \times 586\,\mu\text{m}^2$ with power dissipation about 2.48 mW, and the chip supply voltage can from 1.9 V to 3.3 V. The ramp voltage which linearly rise from 0 V to 2.82 V, and the output frequency is about 500 KHz and 700 KHz stably when the chip supply voltage is fixed at 3.3 V and 2.0 V respectively.

1. INTRODUCTION

Within a variety of high performance power management IC, the PWM-controlled technique is often considered as the main stream of power conversion circuit, for example, high efficiency conversion power supply, motor speed control, etc. [1]. And the PWM modulator is the feedback control core circuit of the switching power converters, it is modulate an analog signal with ramp (sawtooth wave) to a digital signal converter shown in Fig. 1 [2]. For example, a voltage-mode control circuit of PWM power converter is achieved through the error OPA output analog signal voltage (due to input voltage or load current changes) to the non-inverting input of hysteresis comparator with a ramp voltage and produce a different width of the digital control pulse to drive control power transistors. Conventionally, the ramp generator is implemented by the two hysteresis comparators and one S-R latch circuit scheme. In order to achieve a high linearity, reduce the area and the power consumption of the chip. This paper proposes a simple ramp (sawtooth wave) generator with the Schmitt trigger circuit suitable for PWM modulator for switching power converter applications.

This paper is organized as follows. Section 2 gives the architecture and operation principle of ramp generation circuits. The design and implementation of the proposed ramp generator with the Schmitt trigger circuit is discussed in Section 3. Simulation and measured results are included in Section 4. Finally, the conclusion is given in Section 5.

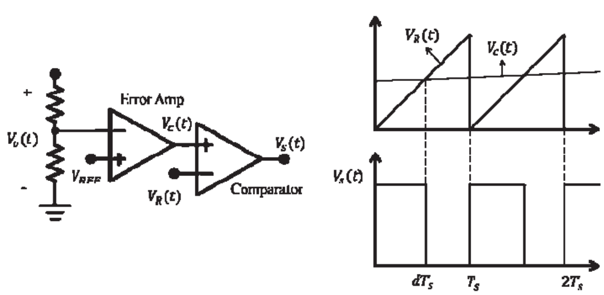

Figure 1: Schematic of PWM modulator for switching power converter with voltage-mode feedback control circuit.

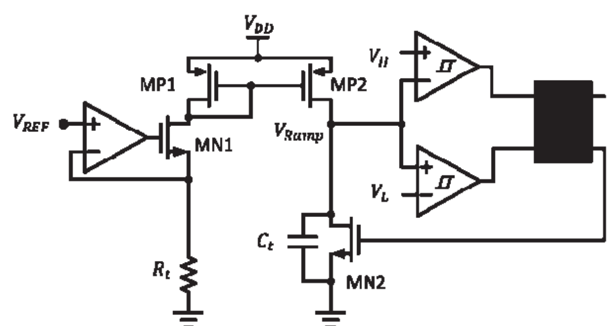

Figure 2: Conventional ramp generator for PWM modulator.

2. ARCHITECTURE AND OPERATION PRINCIPLE OF RAMP GENERATION CIRCUITS

The conventional ramp generator is composed of the voltage-current conversion circuit (V-I converter), current mirror, the two hysteresis comparators, and one S-R latch circuit. This ramp clock generation scheme as shown in Fig. 2 is suitable for the PWM feedback control core circuit of the switching power converters in the switching regulator design [2]. The ramp clock with fixed frequency can be shown as follow derived.

The schematic of the proposed ramp generator circuit shown in Fig. 3 is mainly composed of V-I converter circuit, current mirror and Schmitt trigger circuit. Through a two-stage OPA and a NMOS transistor composed of a V-I converter circuit and the current mirror to generate a more stable current source of the charge and discharge of the capacitor C_t, ($I_o = V_{REF}/R_t$). Then by the Smith trigger circuit control MN2 switch to generates a ramp (sawtooth wave) signal. By using the value of the capacitor C_t and the charge and discharge current flowing through the capacitor C_t to adjust the ramp frequency required by the application circuit [3].

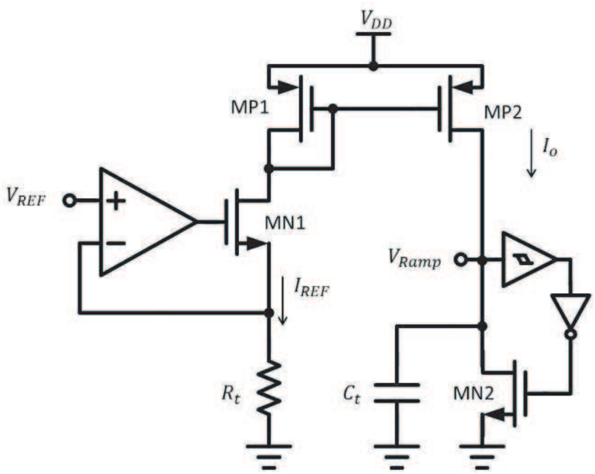

Figure 3: Proposed ramp generator with Schmitt trigger circuit.

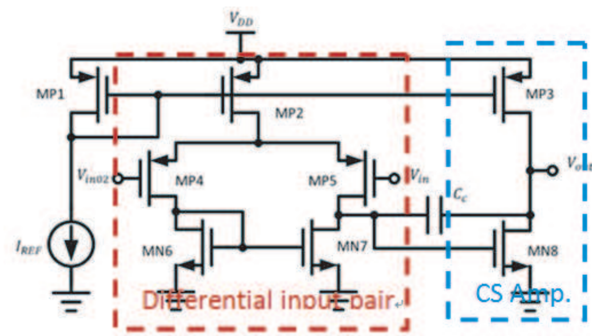

Figure 4: Proposed novel slope compensation circuit.

The ramp frequency is the switching frequency of the PWM power conversion circuit, which can be deduced by the following formula:

$$\because Q = CV = I_o t \quad \text{and} \quad f = \frac{1}{t} = \frac{I_o}{CV} \tag{1}$$

The hysteresis voltage V_{SPH} and V_{SPL} on the Schmitt trigger circuit (Fig. 3) are brought into the Equation (1) [or the voltage difference ($V_H - V_L$) of the two hysteresis comparators of Fig. 2]. Therefore, the ramp clock frequency can be shown as,

$$\therefore f = \frac{V_{REF}}{R_t C_t (V_{SPH} - V_{SPL})} \quad \text{or} \quad f = \frac{V_{REF}}{R_t C_t (V_H - V_L)} \tag{2}$$

3. ANALYSIS AND DESIGN OF PROPOSED RAMP CIRCUIT

In order to achieve a high current accuracy, an operational amplifier V-I converter is used to replace with a cascade of a source follower and a common-source configuration with source degeneration C_t. The two stage PMOS input OPA plays an important role in low power applications, shown in Fig. 4 [4, 5]. The greater the operational amplifier output swing the greater the ability to adapt the change of the input power supply. The high gain range of amplifier is also greater. In order to make the overall OPA have sufficient phase margin, Miller compensation capacitor must be added in the path of second stage CS output feedback to the first PMOS input differential stage output [5, 6].

The PMOS two-stage OPA requires a stable tail bias current source I_{REF}. It is realized through a constant-Gm current references circuit which is independent of supply power and environment temperature [6]. As shown in Fig. 5, the constant-Gm current references circuit is composed of the

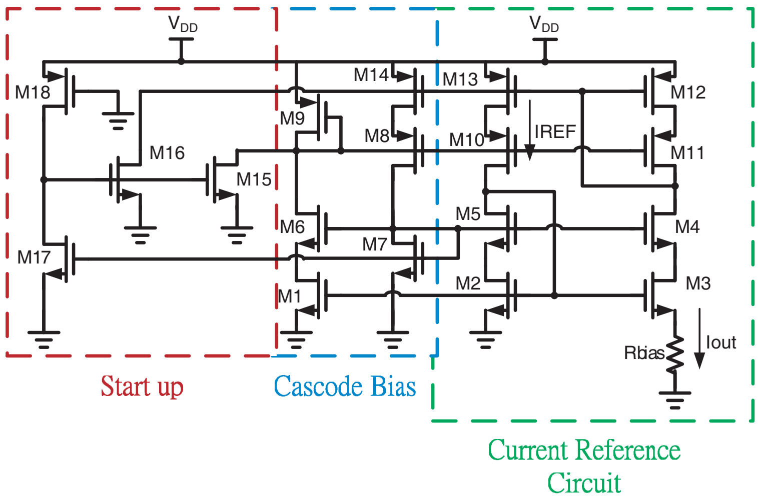

Figure 5: Constant-Gm current reference circuit.

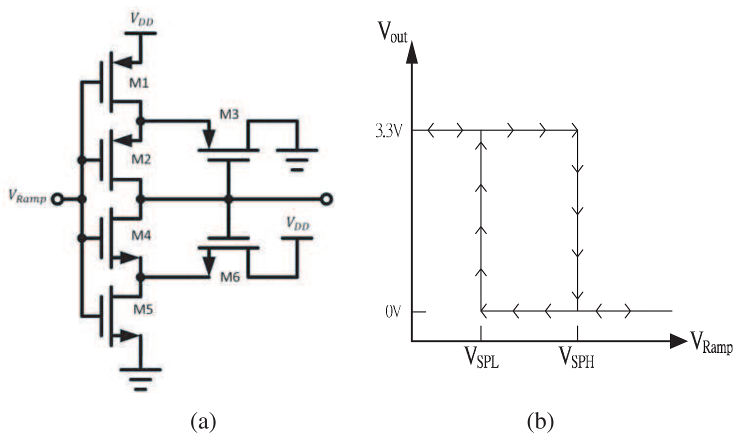

Figure 6: (a) Schmitt trigger circuit; (b) Hysteresis curve.

low voltage current mirror (M2 ∼ M5 and M10 ∼ M13), cascade bias circuit (M1, M6 ∼ M9 and M14) and startup circuit (M15 ∼ M18).

The structure of the proposed ramp generator with Schmitt trigger circuit in this paper replace two hysteresis comparators, where the Schmitt trigger circuit is shown in Fig. 6(a).

The Schmitt trigger circuit operation principle is as follows. When V_{Ramp} rises from zero, M4, M5 is in the cut-off state, the Schmitt trigger circuit output voltage is in the high potential state. When V_{Ramp} rises to $V_{GS4} > V_{TN}$, M4, M5 turns on. And at this time, $V_{Ramp} = V_{SPH}$. When M4 and M5 are turned on so that the Schmitt trigger circuit output voltage is transition to the low state, then the MN2 of Fig. 3 is turned on and the voltage V_{Ramp} of C_t decreases rapidly. When V_{Ramp} drops to V_{SPL}, then M1 and M2 are turned on so that the Schmitt trigger circuit output voltage is switched to the high state, and the MN2 of Fig. 3 is turned off, then the voltage V_{Ramp} of C_t charging rises linearly. Therefore, the hysteresis curve of this Schmitt trigger circuit is shown in Fig. 6(b) [7].

It is known from the above analysis that adjust the aspect ratio of M5 and M6 can obtain the upper trigger voltage V_{SPH} of the Schmitt trigger circuit, and adjust the aspect ratio of M1 and M3 can obtain the lower trigger voltage V_{SPL} of the Schmitt trigger circuit as shown in Equation (3).

$$\frac{\beta_5}{\beta_6} \approx \left[\frac{V_{DD} - V_{SPH}}{V_{SPH} - V_{TH,n}}\right]^2 \quad \text{and} \quad \frac{\beta_1}{\beta_3} \approx \left[\frac{V_{SPL}}{V_{DD} - V_{SPL} - V_{TH,p}}\right]^2 \tag{3}$$

4. SIMULATION AND MEASUREMENT RESULTS

After summarizing the analysis of all component circuits, the full circuit and the electronic microscope layout of the proposed ramp generator with Schmitt trigger circuit are shown in Figs. 7 and 8. And the chip size is about $0.672 \times 0.586\,\text{mm}^2$ and power consumption is about 2.48 mW that realized using TSMC 0.35 μm CMOS 2P4M process [8].

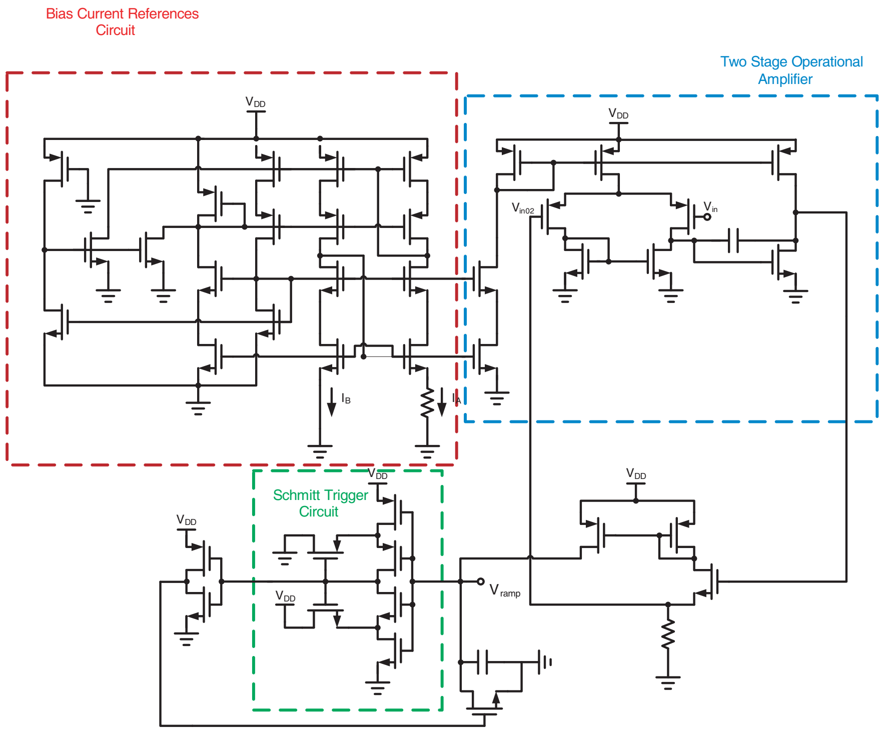

Figure 7: Proposed ramp generator with Schmitt trigger circuit.

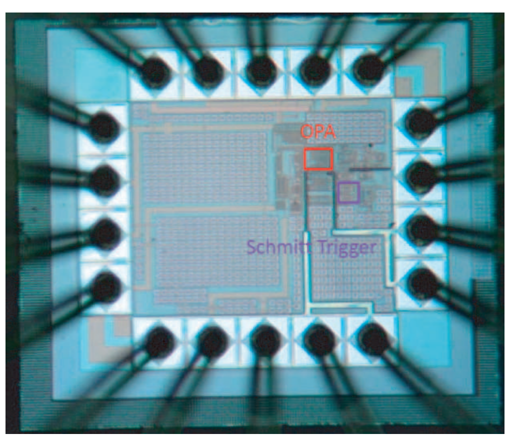

Figure 8: Microscope layout of proposed ramp generator.

In the ramp generator with Schmitt trigger circuit, the reference current source is mainly provided as a bias tail current for the two stage PMOS input OPA circuit. The current is designed to be about 30 μA. As shown in Fig. 9, the output current of the reference current source is stable after about 40 μs. The M15 ∼ M18 in Fig. 5 are the start-up circuit of the current references circuit, its purpose is only current pull up the low voltage current mirror (M2 ∼ M5 and M10 ∼ M13), then M16 and M15 turn off. As shown in Fig. 10, when power ON in 5 μs, the voltage $V_{GS15}(V_{GS16})$ rise up, and about 20 μs the voltage $V_{GS15}(V_{GS16})$ down to ground.

Figure 11 shows the hysteresis curve and its output voltage of the Schmitt trigger circuit. When V_{Ramp} rises from zero [the Schmitt trigger circuit output voltage is at the high potential

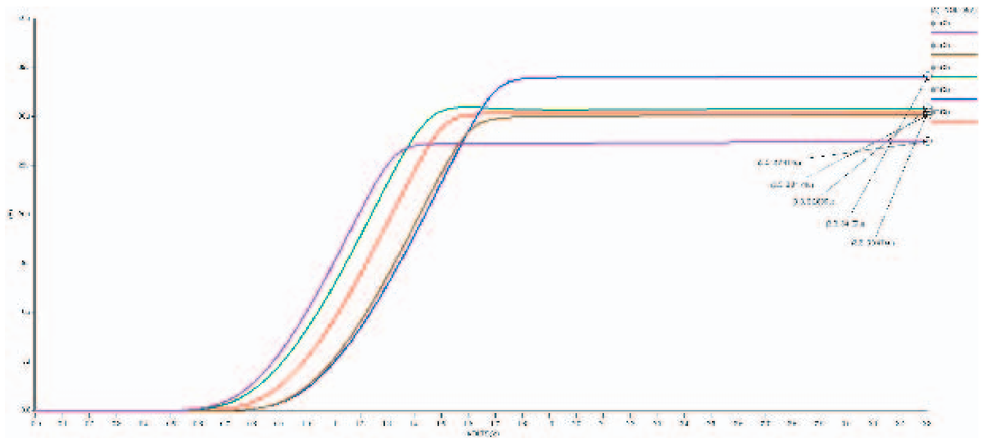

Figure 9: Bias current of constant-Gm current references circuit.

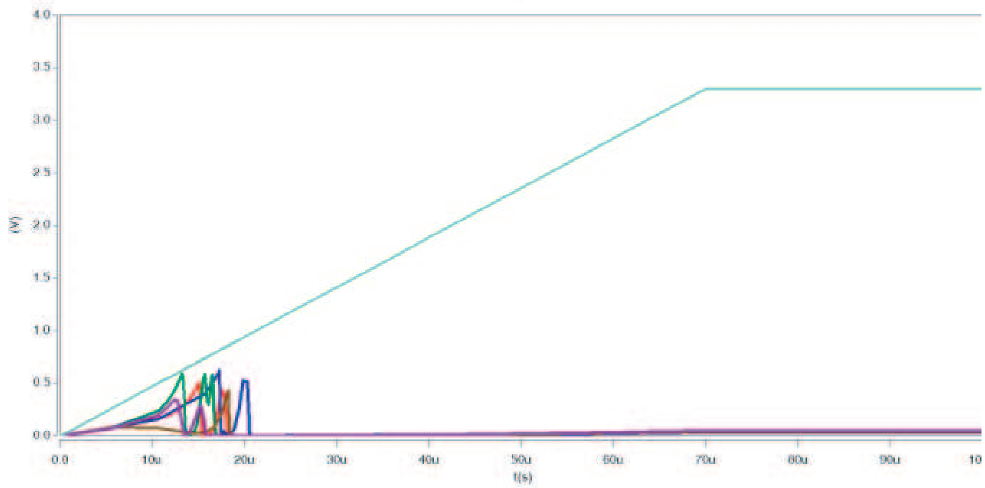

Figure 10: Transient response of start-up circuit.

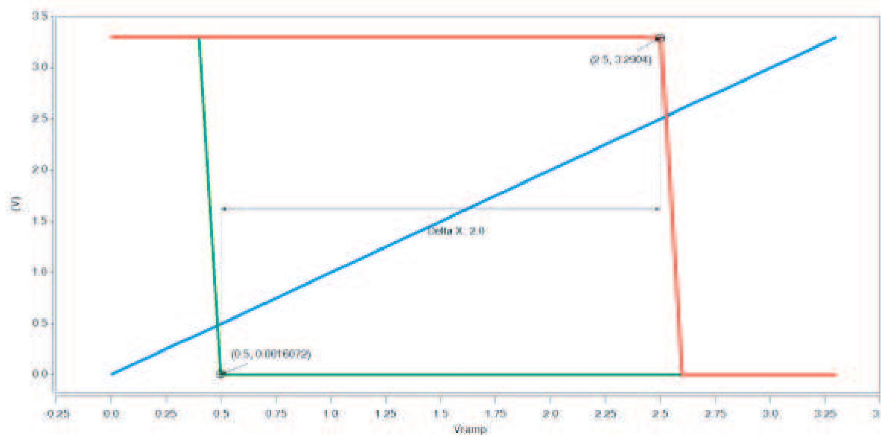

Figure 11: Hysteresis curve of Schmitt trigger circuit.

state (3.2 V)], until V_{Ramp} rises more than 2.5 V, and the Schmitt trigger circuit output voltage is transition to the low state (0 V). When V_{Ramp} drops to 0.5 V, the Schmitt trigger circuit output voltage is switched to the high state (3.2 V). Therefore, the trigger voltage V_{SPH} and V_{SPL} are about 2.5 V and 0.5 V, respectively.

Figure 12 shows the output ramp frequency of the proposed the ramp generator with Schmitt trigger circuit is about 500 KHz and its amplitude voltage V_{p-p} is 2.58 V under the different corner simulation results.

From the measurement result in Fig. 13, it shows that the output ramp frequency of the proposed ramp generator with Schmitt trigger circuit is 500.1 KHz and peak amplitude voltage V_{p-p} is 2.82 V under power supply voltage is 3.3 V.

And from Fig. 14 shows the measurement result that the output ramp frequency of the chip is 700.5 KHz and peak amplitude voltage V_{p-p} is 1.96 V under power supply voltage is 2.0 V.

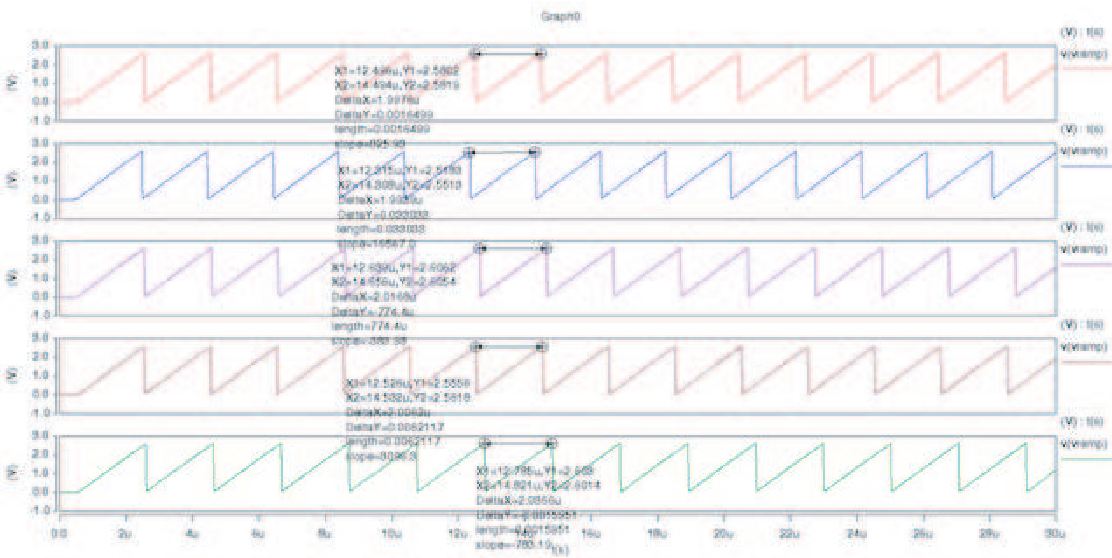

Figure 12: Ramp frequency for proposed ramp generator circuit.

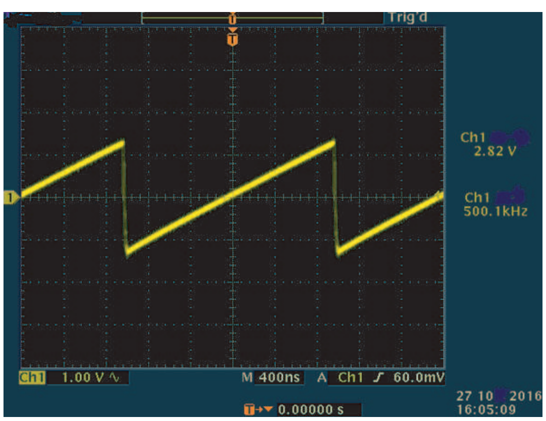

Figure 13: Ramp frequency for chip measurement ($V_{DD} = 3.3$ V).

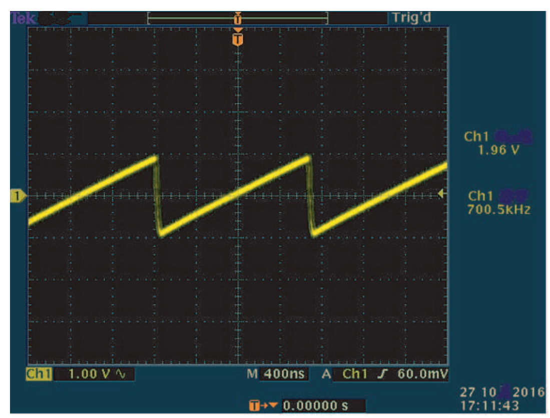

Figure 14: Ramp frequency for chip measurement ($V_{DD} = 2.0$ V).

5. CONCLUSION

Based on the aforementioned discussions, we can conclude that the implemented the ramp generator with Schmitt trigger circuit has the chip size is $671.99 \times 586\,\mu\text{m}^2$ with power dissipation about 2.48 mW, and the chip supply voltage can from 1.9 V to 3.3 V. The ramp voltage which rise from 0 V to 2.82 V linearly, and the output frequency is about 500 KHz and 700 KHz stably when the chip supply voltage is fixed at 3.3 V and 2.0 V respectively. Finally, simulation and measured results shows the ramp generator with Schmitt trigger circuit suitable for PWM modulator for switching power converter or the supply modulator of a wideband wireless transmitter applications.

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