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DESIGN OF A THRESHOLD AUTOMATIC COMPENSATION CIRCUIT FOR A VOLTAGE CONTROLLED OSCILLATOR USING A SCHMITT-TRIGGER CIRCUIT WITH CMOS INVERTERS

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Abstract. *A voltage controlled oscillator (VCO) is an important circuit which is applied for phase locked loop (PLL) and various measuring devices. When we constitute the VCO based on the Miller integrator and the Schmitt-trigger circuit with operational amplifiers, the VCO has a problem that the relation between the oscillating frequency and the control voltage does not agree with the theoretical value by the delay of the operational amplifier. To solve this problem, we have already proposed the VCO using the Schmitt-trigger circuit with complementary metal-oxide-semiconductor (CMOS) inverters. However, the variation of the threshold voltage of the CMOS inverter affects the direct current (DC) component of the triangular wave. In this paper, we propose a VCO using a novel threshold automatic compensation circuit. Owing to the threshold automatic compensation circuit, the proposed circuit can realize the triangular wave around 0V. Furthermore, feasibility and effectiveness of the proposed circuit are demonstrated through the experiment using fabricated integrated circuit (IC) chips.*
Keywords: VCO, Schmitt-trigger, CMOS inverter, Miller integrator

1. **Introduction.** A voltage controlled oscillator (VCO) is an important circuit which is applied for phase locked loops (PLLs) and various measuring devices, and it has various types [1-5]. When the VCO is designed in a simplified form, operational amplifiers or CMOS logic fates are generally used. However, a parameter that determines the oscillating frequency includes the threshold voltage when the complementary metal-oxide-semiconductor (CMOS) logic gate is employed. For this reason, the VCO has a problem that the oscillating frequency is varied by ambient temperature and so on [6].

On the other hand, the reversal level of the circuit operation is decided by external resistances regardless of ambient temperature when the operational amplifier is employed. Therefore, in this case, the VCO can achieve the stable operation [7]. However, the output of a triangular wave increases higher than the setting voltage when the Schmitt-trigger circuit is constituted by the operational amplifier. As a result, the VCO has a problem that the relation between the oscillating frequency and the control voltage does not agree with the theoretical value by the delay of the operational amplifier. To solve this problem, we have already proposed the VCO using the Miller integrator with an operational amplifier and the Schmitt-trigger circuit with CMOS inverters [8]. The VCO reported in [8] is less affected by the delay of circuit elements as the Schmitt-trigger circuit is constituted by using CMOS inverters even when the oscillating frequency is high. Therefore, the relation between the control voltage and the oscillating frequency shows good linearity in this VCO. Furthermore, by adding a threshold automatic compensation circuit to the VCO, the threshold voltage of the CMOS inverter can be kept at 0V automatically. Therefore, the direct current (DC) component of the triangular wave is not affected by the variation of the threshold voltage of the CMOS inverter.

In this paper, we propose a VCO using a novel threshold automatic compensation circuit. Owing to the threshold automatic compensation circuit, the proposed circuit can realize the triangular wave around 0V. Furthermore, in the relationship between the control voltage and the oscillating frequency, the proposed circuit shows better linearity than the conventional circuit. Concerning fabricated integrated circuit (IC) chips of the proposed circuit, the characteristics of the proposed circuit are clarified.

2. **Circuit Configurations.** First, we describe the problem of the conventional VCO using the Miller integrator and the Schmitt-trigger circuit. Figure 1 shows the circuit configuration of the conventional VCO using the Miller integrator and the Schmitt-trigger circuit with an operational amplifier. This circuit converts the triangular wave of the Miller integrator into the rectangular pulse by utilizing the hysteresis characteristic of the Schmitt-trigger circuit that has the positive threshold V_H and the negative threshold V_L. Therefore, the amplitude of the triangular wave increases higher than the setting voltage when the oscillating frequency is high. As a result, the relation between the control voltage and the oscillating frequency does not agree with the theoretical value.

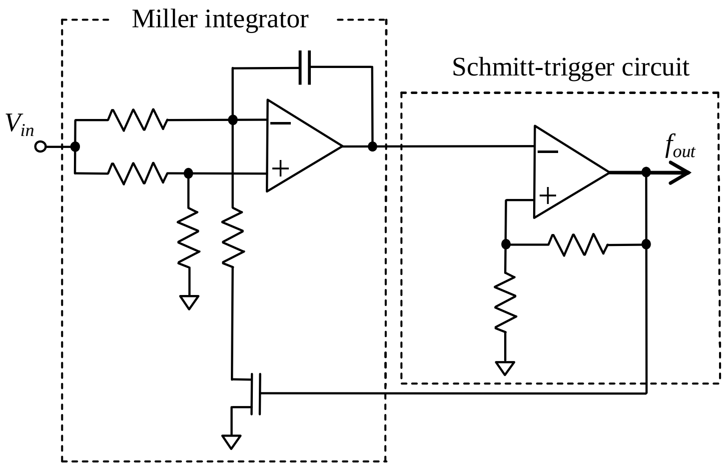


FIGURE 1. Circuit configuration of the conventional VCO based on the Miller integrator and the Schmitt-trigger circuit with the operational amplifier

Figure 2 shows the VCO which solves the delay of the operational amplifier by the Schmitt-trigger circuit using CMOS inverters. In this circuit, the variation of the threshold voltage of the CMOS inverter affects the DC component of the triangular wave. Therefore, it is difficult to realize the triangular wave around 0V. However, by adding a threshold automatic compensation circuit shown in Figure 3, we have already solved this problem in [8]. The VCO of Figure 3 can offer the triangular wave around 0V, because the threshold automatic compensation circuit is added to the source of n-MOS of the first CMOS inverter in the Schmitt-trigger circuit.

Figure 4 shows the circuit configuration of the proposed VCO with the threshold automatic compensation circuit using the Miller integrator with an operational amplifier

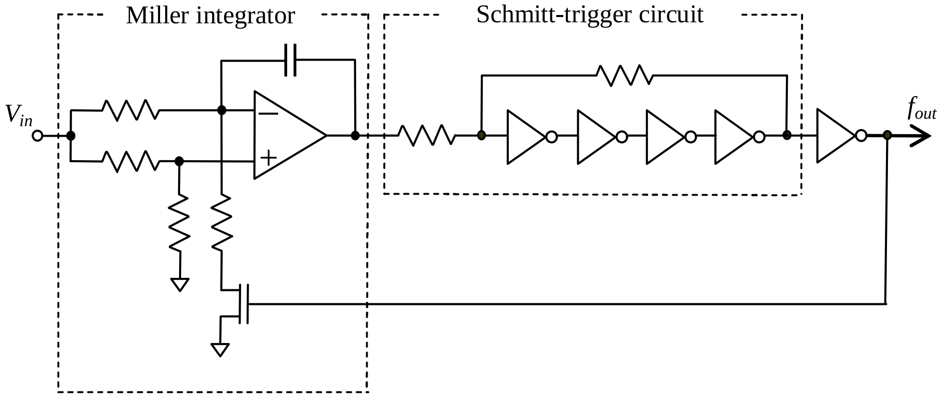


FIGURE 2. Circuit configuration of the conventional VCO based on the Schmitt-trigger circuit with CMOS inverters

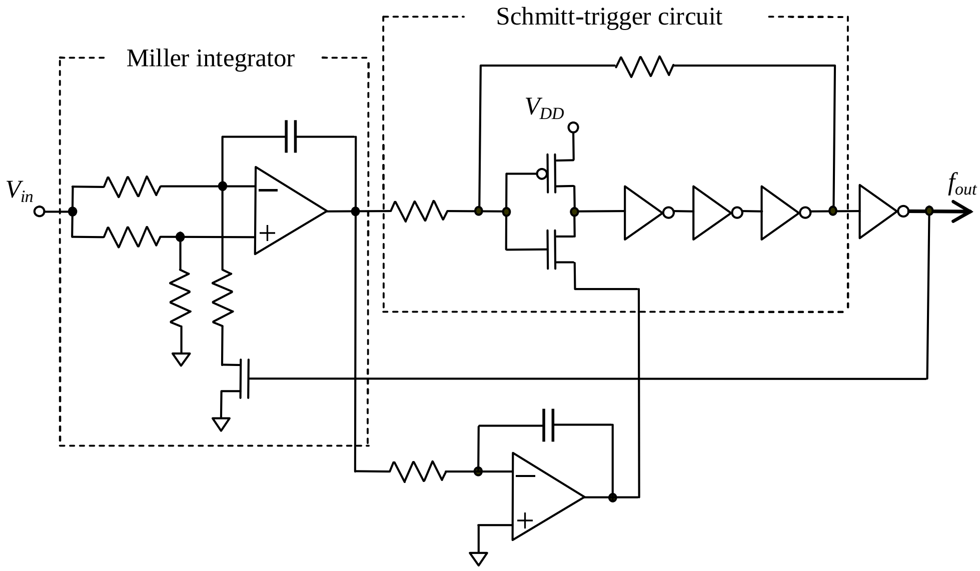


FIGURE 3. Circuit configuration of the conventional VCO with the threshold automatic compensation circuit

and the Schmitt-trigger circuit with CMOS inverters. In Figure 4, A_1, R_1-R_4, and C_1 are an operational amplifier, resistances, and a capacitance for the Miller integrator, respectively. M_2, M_3, N_1-N_3, R_5, R_6 are MOS transistors, CMOS inverters, and resistances for the Schmitt-trigger circuit. N_4 and M_1 are the CMOS inverters to control the charge and discharge operation using the output of the Miller integrator and the MOS transistor which has the operation of the switch. A_2, A_3, M_4, R_7-R_9, C_2 are operational amplifiers, a MOS transistor, resistances, and a capacitance for the threshold automatic compensation circuit. The capacitance C_2 of the threshold automatic compensation circuit is designed sufficiently bigger than the capacitance C_1.

3. **Operation Analysis.**

3.1. **Oscillating operation.** When the output of N_4 is in a high level, M_1 is turned "ON". Then, the electric charge stored in C_1 is discharged and the output of A_1 increases linearly by the Miller effect. The output of N_4 becomes a low level when the output of A_1 reaches to the positive threshold voltage of the Schmitt-trigger circuit V_H. By this operation, M_1 is turned "OFF", C_1 is charged, and the output of A_1 decreases linearly by the Miller effect. When the output of A_1 reaches to the negative threshold voltage V_L, the

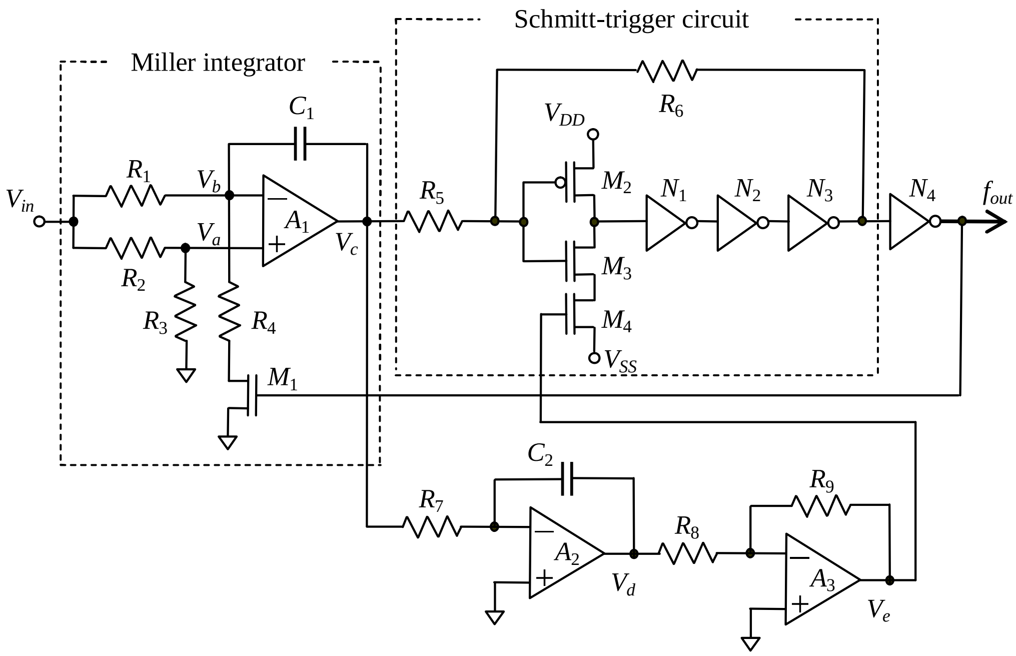


FIGURE 4. Circuit configuration of the proposed VCO

output turns over again and returns to the original state. The proposed VCO performs the oscillating operation by repeating these operations.

3.2. **Relation between the control voltage and the oscillating frequency.** The operation of the part of the Miller integrator is described. In the Miller integrator, we design the resistances R_1-R_4 to satisfy $R_1 = 2R_4$ and $R_2 = R_3$. First, V_a and V_b are treated as imaginary short, and expressed as:

$$V_a = V_b. \tag{1}$$

From $R_2 = R_3$, V_a is expressed as follows.

$$V_a = \frac{1}{2}V_{in}. \tag{2}$$

When the MOS transistor M_1 is "OFF", the current which flows into C_1, I_C, is given by:

$$I_C = \frac{V_{in} - V_a}{R_1} = \frac{V_{in} - \frac{1}{2}V_{in}}{R_1} = \frac{V_{in}}{2R_1}. \tag{3}$$

On the other hand, when the MOS transistor is "ON", the current I_C is given by:

$$I_C = \frac{V_{in} - V_a}{R_1} - \frac{V_a}{R_4} = \frac{V_{in} - \frac{1}{2}V_{in}}{R_1} - \frac{V_a}{\frac{1}{2}R_1} = -\frac{V_{in}}{2R_1}. \tag{4}$$

Therefore, the output voltage of the Miller integrator V_c increases or decreases linearly, because the capacitance C_1 is charged or discharged by the constant current in proposition to the control voltage V_{in}.

Next, we describe the Schmitt-trigger circuit. In Figure 4, a pair of MOS transistors M_2 and M_3 can be treated as an inverter although the source of M_3 is connected to the drain of M_4 to compensate the threshold voltage. When the threshold voltage of the inverter consisting of M_2 and M_3 is V_{th}, two threshold voltages of the Schmitt-trigger circuit, V_H and V_L, are expressed as:

$$V_H = \frac{R_5 V_{DD}}{R_6} + \left(1 + \frac{R_5}{R_6}\right) V_{th} \tag{5}$$

and

$$V_L = -\frac{R_5 V_{DD}}{R_6} + \left(1 + \frac{R_5}{R_6}\right) V_{th}. \tag{6}$$

Here, let us derive the oscillating frequency f_{out}. When the output of the Schmitt-trigger circuit becomes a high level, the time of the half period t_{w1} is expressed as:

$$t_{w1} = \frac{4R_5 R_1 C_1 V_{DD}}{R_6 V_{in}}. \tag{7}$$

Also the oscillating frequency is expressed as:

$$f_{out} = \frac{R_6 V_{in}}{8R_5 R_1 C_1 V_{DD}}, \tag{8}$$

because the half period t_{w2} can be obtained in the same way. From Equation (8), the oscillating frequency f_{out} which is proportional to the input voltage V_{in} can be obtained.

3.3. **Operation of the threshold automatic compensation.** In this subsection, we describe the operation of the threshold automatic compensation. In the threshold automatic compensation, V_c is the triangular wave which has the DC component with $(1 + R_6/R_5)V_{th}$ when the threshold voltage of the inverter consisting of M_2 and M_3 is V_{th}. Therefore, if V_{th} is negative, the output of the Miller integrator consisting of R_7, C_2, and A_2, V_d, increases. When the V_d is connected to the inverting amplifier circuit consisting of R_8, R_9, and A_3, the output voltage V_e decreases. By inputting V_e to the gate of M_4, the threshold voltage V_{th} of the inverter consisting of M_2 and M_3 increases. Oppositely, if V_{th} is positive, the output of the Miller integrator V_d decreases. When the V_d is connected to the inverting amplifier circuit, the output voltage V_e increases. By inputting V_e to the gate of M_4, the threshold voltage V_{th} of the inverter consisting of M_2 and M_3 decreases. By these operations, the threshold voltage of the inverter consisting of M_2 and M_3 can be kept at 0V and obtained the triangular wave around 0V.

4. **Experimental Results.** By using the Onsemi-Sanyo 0.8μm CMOS process, we fabricated the following four types of VCOs into an IC chip: 1) The conventional VCO using the Miller integrator and the Schmitt-trigger with an operational amplifier, 2) The conventional VCO using the Schmitt-trigger with CMOS inverters, 3) The conventional VCO with the threshold automatic compensation circuit, and 4) The proposed VCO.

Figure 5 shows the layout of the proposed VCO. In this experiment, in order to set 800kHz maximum frequency and 50% duty cycle, the parameters are determined as follows: $R_1 = 60\text{k}\Omega$, R_2-$R_4 = 30\text{k}\Omega$, $R_5 = 10\text{k}\Omega$, $R_6 = 20\text{k}\Omega$, $R_7 = 600\text{k}\Omega$, $R_8 = 30\text{k}\Omega$, $R_9 = 30\text{k}\Omega$, $C_1 = 5\text{pF}$, and $C_2 = 40\text{pF}$. Also the supply voltage V_{DD} and V_{SS} are set to 2.5V and -2.5V, respectively. Figure 6(a) shows the measured outputs when the control

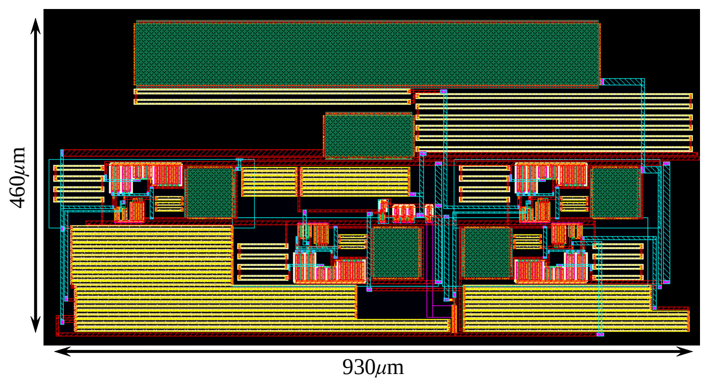
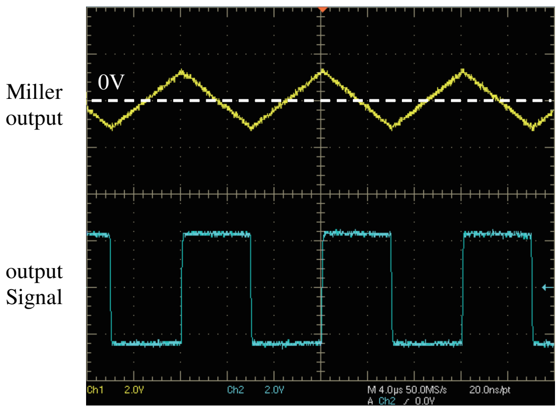
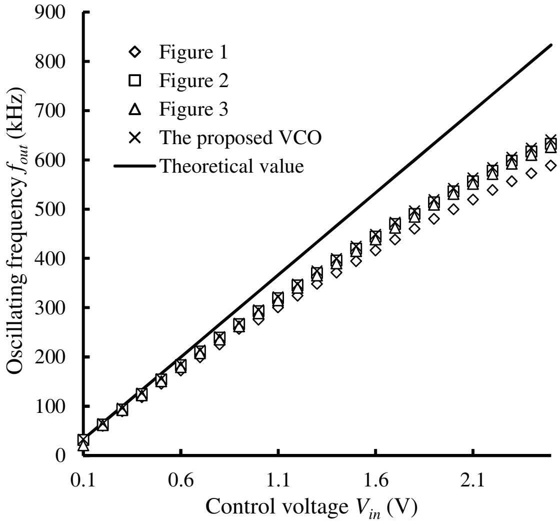


FIGURE 5. Layout of the proposed VCO



(a) Measured outputs of the proposed VCO



(b) V-f characteristic of the experimental circuit

FIGURE 6. Experimental results of the proposed VCO

voltage V_{in} was set to 1.0V. From this figure, the validity of the circuit design can be confirmed.

Figure 6(b) shows the measured V-f characteristic of the experimental circuits when the control voltage is varied from 0V to 2.5V. From this figure, we can confirm that the proposed VCO shows good linearity although the V-f characteristic is slightly affected by the gate transit time. Also, the conventional circuit of Figure 3 has a problem that source voltage of the CMOS inverter of the n-MOS transistor varies, because the source terminal is connected to the operational amplifier. However, since the variation of the source voltage does not affect the proposed circuit by connecting the source terminal of the n-MOS transistor to V_{SS}, it is possible to achieve a stable operation.

5. **Conclusion.** In this paper, we proposed a novel VCO using a threshold automatic compensation circuit. Owing to the Schmitt-trigger circuit with CMOS inverters, the proposed circuit showed a good V-f characteristic even if the oscillating frequency is high. Furthermore, the triangular wave around 0V was realized by the threshold automatic compensation circuit.

We fabricated the IC chip of the proposed VCO using the Onsemi-Sanyo 0.8μm CMOS process, and confirmed the circuit design through the experiments using the fabricated IC chip. In the experiment, the V-f characteristic of the proposed circuit showed better linearity than that of the conventional circuits.

In future work, we are going to plan to more improve the linearity of V-f characteristic of the proposed circuit.

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