A MOS Temperature Compensation Function Generator for TCXO Using Differential MOS Multipliers

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Abstract— **The temperature compensated crystal oscillator (TCXO) is widely used as a stable frequency source of mobile communication equipment. A TCXO is composed of a temperature sensor, compensation voltage generator and voltage controlled crystal oscillator. The compensation function generator is a key component of a TCXO. In this paper, we have proposed a new MOS temperature compensation function generator using analog MOS multipliers. We have evaluated the performance of the proposed compensation function generator by ADS simulation. Simulation showed that the compensation function generator had very small temperature dependence itself and it could generate cubic function of temperature.**

I. INTRODUCTION

The temperature compensated crystal oscillator (TCXO) is widely used as a stable frequency source of mobile communication equipment. A TCXO is composed of a temperature sensor, compensation voltage generator and voltage controlled crystal oscillator. A temperature dependence of oscillation frequency of the voltage controlled oscillator using AT-cut crystal resonator is a cubic function of temperature. The compensation function generator is a key component of a TCXO. There have been developed a lot of techniques to generate the cubic function for TCXO [1][2][3] . A digital-TCXO (DTCXO) stores the compensation voltages for certain temperature range on a memory. DTCXO is suitable for high precision compensation but has the drawback of phase-jumping in frequency[3]. Dr. Nemoto et al. developed an analog CMOS TCXO in which compensation voltage was generated by variable gain amplifiers[4]. We proposed a compensation function generator using analog MOS multipliers[5][6]. Dr. Lim et al. presented a CMOS compensation function generator using analog multipliers at IFCS2008, too[7]. Usually an analog multiplier has temperature dependence itself and we introduced the method to adjust their multiplication factors in three temperature range[6]. Dr. Lim introduced a pair of linear inputs to the multiplier to cancel the temperature dependence of multipliers[7].

In this paper, we have proposed a new MOS compensation function generator for TCXO using analog MOS multipliers. We evaluated the performance of the proposed compensation function generator by ADS simulation.

II. CIRCUIT STRUCTURE AND PRINCIPLE OF OPERATION

Fig 1 shows a block diagram of TCXO. Fig. 2 shows the compensation function generator circuit. The compensation function generator is made by two temperature independent multipliers and a voltage adder. The compensation function is the sum of a cubic and a linear function of temperature. The cubic function is made by two multipliers. Fig 3 shows the circuit of adder. Resistances of $R_1 \sim R_4$ are determined to satisfy $R_1 + R_2 = R_3 + R_4$. Putting the sensor output into V_1 terminalof the adder and the cubic function of sensor output into V_2 terminal, the output of the adder becomes

$$V_{out} = -\frac{R_2}{R_1}V_{temp} + \frac{R_4}{R_1}V_{temp}^3 \qquad (1)$$

where V_{temp} denotes the sensor output voltage.

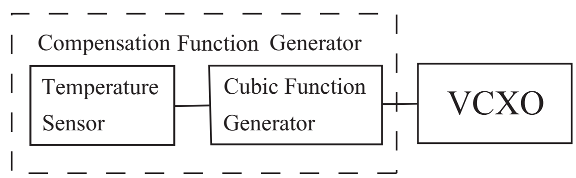

Fig. 1. Block Diagram of TCXO.

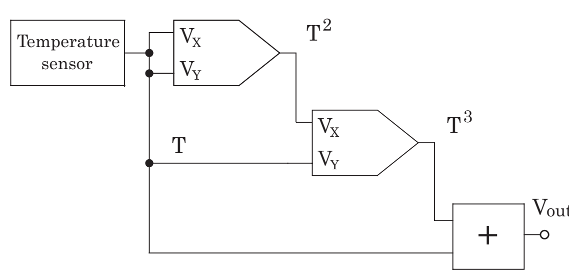

Fig. 2. Compensation function generator.

Fig.4 shows the circuit structure of the temperature independent multiplier[8][9]. This multiplier consists of two element multipliers MUL1 and MUL2 and an operational amplifier. The outputs of multiplier MUL1 and MUL2 are connected

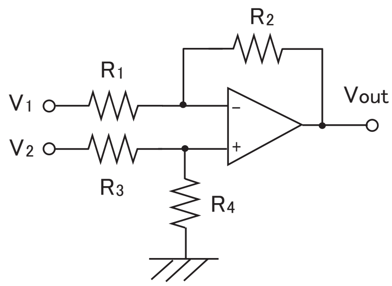

Fig. 3. Adder

to the inputs of the operational amplifier. The output of the operational amplifier is fed back to the one of the input of MUL2.

The element multipliers MUL1 and MUL2 have the same structure. Fig.5 shows the circuit structure of the element multiplier. These multipliers are called MOS resistive circuits (MRCs).

Two inputs of the operation amplifier are assumed to be zero. When all MOS FETs are operating in linear region, the drain currents of M1 and M2 are expressed as follows.

$$I_{D1} = 2K_1(V_{g1} - V - V_T - \frac{V_1 - V}{2})(V_1 - V) \quad (2)$$

$$I_{D2} = 2K_1(V_{g2} - V - V_T - \frac{V_1 - V}{2})(V_1 - V) \quad (3)$$

where K_1 is the transconductance parameter and V_T is the threshold voltage of MOS FETs in MUL1.

Substracting these equations, the following equation is obtained.

$$I_{D1} - I_{D2} = 2K_1(V_{g1} - V_{g2})(V_1 - V) \quad (4)$$

Similarly, $I_{D3} - I_{D4}$ is obtained as follows.

$$I_{D3} - I_{D4} = 2K_1(V_{g1} - V_{g2})(V - V_2) \quad (5)$$

On the other hand, output current I_3 and I_4 are

$$I_3 = I_{D1} + I_{D3} \quad (6)$$

$$I_4 = I_{D2} + I_{D4} \quad (7)$$

From (4)(5)(6)(7),

$$\begin{aligned} I_3 - I_4 &= (I_{D1} - I_{D2}) + (I_{D3} - I_{D4}) \\ &= 2K_1(V_{g1} - V_{g2})(V_1 - V_2) \end{aligned} \quad (8)$$

is obtained.

On the other hand,

$$V_{g1} - V_{g2} = V_y \quad (9)$$

$$V_1 - V_2 = V_X \quad (10)$$

Substituting (9) and (10) into (8), we obtain

$$I_3 - I_4 = 2K_1 V_X V_Y \quad (11)$$

Similary, the difference of I'_3 and I'_4 is obtained as follows.

$$I'_3 - I'_4 = 2K_2 V_Z V_{out} \quad (12)$$

where K_2 is the transconductance parameter of MOS FETs in MUL2.

The input currents of the operational amplifier are assumed to be zero,

$$I_3 + I'_3 = 0 \quad (13)$$

$$I_4 + I'_4 = 0 \quad (14)$$

are obtained.

Substractiong these two equations, we obatin

$$I_3 - I_4 = -(I'_3 - I'_4) \quad (15)$$

Substituting (11) and (12),

$$V_{OUT} = K V_X V_Y \quad (16)$$

where, K is the overall gain factor and is described by the following equation.

$$K = \frac{K_1}{K_2}\frac{1}{V_Z} \quad (17)$$

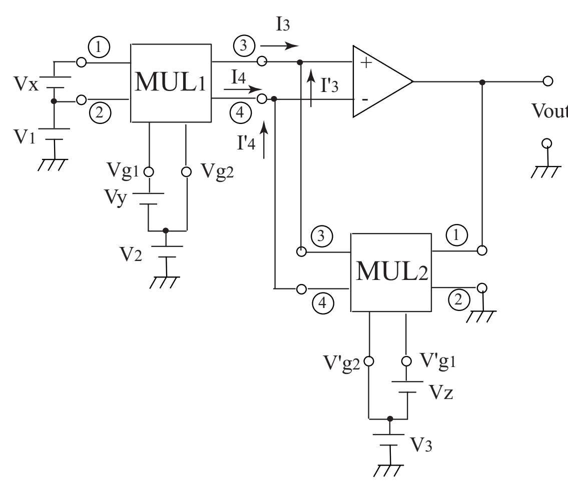

Fig. 4. Temperature independent multiplier.

These equations show that the circuit shown in Fig.4 acts as the multiplier when we select V_X and V_Y as inputs. And the gain factor can be controlled by variable V_Z.

K_1 and K_2 can be expressed by the following equations using the unit transconductance parameter K_0 and aspect ratios of MOS FETs of element multipliers.

$$K_1 = A_1 K_0 \frac{W_1}{L_1} \quad (18)$$

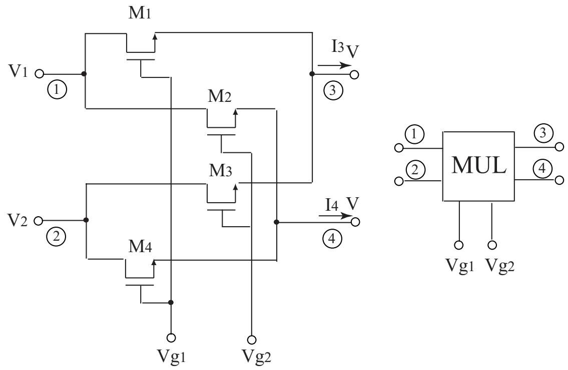

Fig. 5. Element multiplier (MOS resistive circuie).

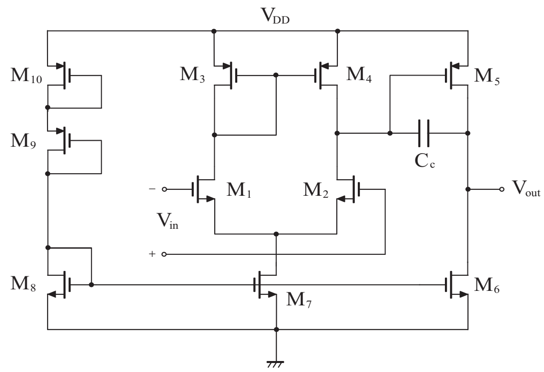

Fig. 6. Operational amplifier

$$K_2 = A_2 K_0 \frac{W_2}{L_2} \tag{19}$$

where A_1 and A_2 are the constants, L_1 and L_2 are channel lengths and W_1 and W_2 are channel widths of FETs in MUL1 and MUL2.

Therefore, the overall gain factor K is transformed to the following equation.

$$K = \frac{A_1 \dfrac{W_1}{L_1}}{A_2 \dfrac{W_2}{L_2}} \frac{1}{V_Z} \tag{20}$$

Using a simple model, K_0 is approximately equal to $\mu_0 C_{0X}$, with μ_0 as the surface mobility and C_{0X} as the gate capacitance per unit area. As μ_0 depends on temperature, K_1 and K_2 change with temperature. But, K does not depend on temperature because the transconductance parameters of element multipliers are cancelled out in (20).

Standard two-stage amplifier circuit is used for the operational amplifier. Fig. 6 shows the circuit of the operational amplifier[10].

III. Evaluation by simulation

Simulations have been made to verify the operation of the temperature independent multiplier. $1\mu m$ process was used. Fig.7 shows the relation between V_{out} and V_X when V_Y is changed as parameter. It can be seen that V_{out} is the product of V_X and V_Y and this circuit is operating as a multiplier. Fig.8 shows the relation between V_{out} and V_X when the gain factor is changed by V_Z. It is confirmed that the gain factor changes proportionally to the inverse of V_Z.

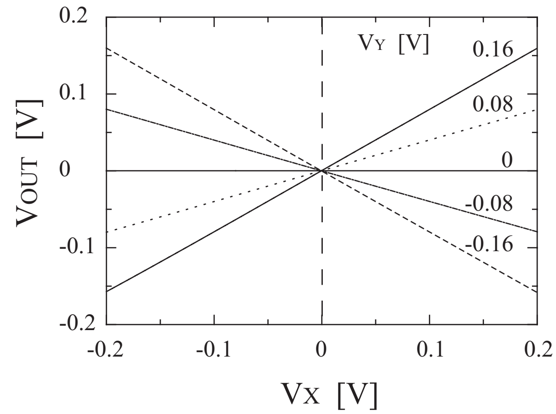

Fig. 7. DC transfer characteristics.

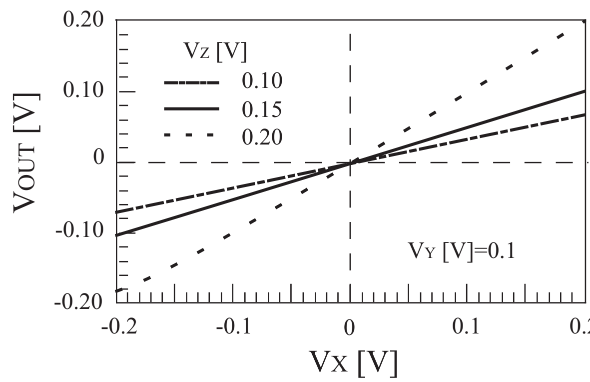

Fig. 8. Gain variation.

Fig.9 shows the temperature dependence of the output voltage. Temperature is varied from −30 °Cthrough 80 °C. The fractional deviation of the output voltage is less than 0.25%.

Fig.10 shows the power supply voltage dependence of the output voltage. Power supply voltage is varied ±10%. The fractional deviation of the output voltage is less than 0.5%. Fig.11 shows the process parameter dependence of the output voltage. Three MOS model parameters, FF, SS and normal, are used for simulation. The FF model is a short-rise time model and the SS model is a long-rise time model. The fractional deviation of the output voltage is less than 1.0%.

Fig.12 shows the output voltage of the compensation function generator. Pure cubic function is obained. This figure shows that the shape of the compensation function can be changed by varying the value of R_4.

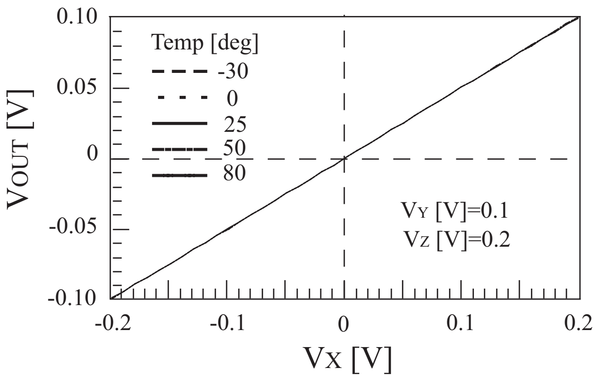

Fig. 9. Temperature dependence.

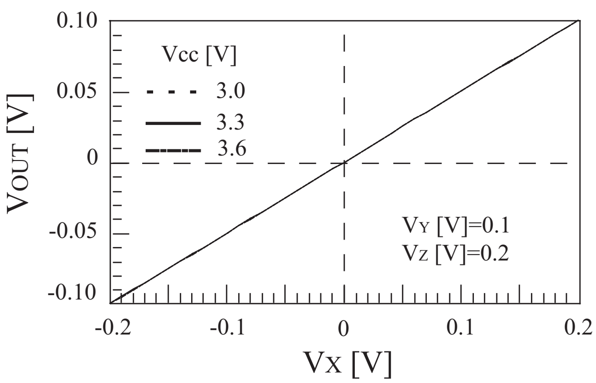

Fig. 10. Supply voltage dependence.

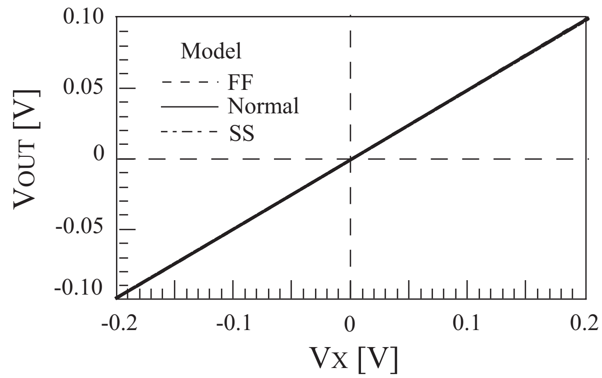

Fig. 11. Process parameter dependence.

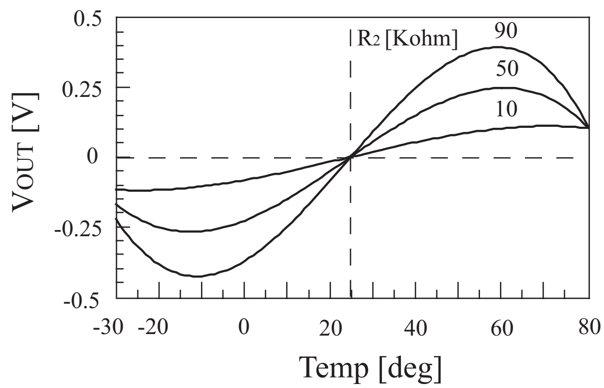

Fig. 12. Compensation function.

IV. Conclusion

We have proposed a new MOS temperature compensation function generator for TCXO. The proposed temperature compensation generator consists of two temperature independent multipliers and an operational amplifier. Simulation showed that temperature independent multiplier has very small dependence on temperature, power supply voltage, and process parameter variation. And it also showed that pure cubic function of temperatue could be obtained by the proposed compensation funcion generator.

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