CCII−based TCXO using a Thermistor Network

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Abstract: - This paper presents the design of a temperature compensated crystal oscillator(TCXO) based on a second generation current conveyor(CCII) and a thermistor network. The CCII is implemented by modified Fabre-Normand circuit. The cubic function of an AT-cut crystal is compensated using thermistors with temperature coefficients of opposite sign. The designed CCII was fabricated using 0.25㎛ standard CMOS process and the thermistor network was implemented off-chip. The measured frequency deviation was ±4ppm for the temperature range from -20℃ to 70℃.

Key-Words: - TCXO, Crystal Oscillator, CCII, Current Conveyor

1 Introduction

Recently, a PLL(Phase Locked Loop) is widely used in modern communication systems, portable wireless systems, and precision measurement systems. There is an increasing demand for a precise reference frequency. As a result, most PLLs have used crystal oscillators because crystals possess a high degree of frequency stability and high Q-factor. However, the resonance frequency of the crystal still changes with the temperature. A crystal oscillator that adopts this frequency stabilization technique is referred to as a TCXO[1]. TCXOs can be classified into analog type and digital type. The DTCXOs(Digital TCXOs) use the data in ROMs for temperature compensation. In recent years, DTCXOs are gaining popularity due to the ease of integration into standard CMOS process. But the capacitance in the oscillation circuit are varied in discrete steps in DTCXOs. As a result, there is a potential of the phase-jumping phenomenon to occur.

On the other hand, the TCXOs of analog type use a temperature compensation network that consists of thermistors and resistors. However it is hard to downsize these TCXOs because the thermistor isn't suitable for integration. But, the analog TCXO can be made small and the phase-jumping phenomenon doesn't happen because the analog TCXO can change the frequency continuously. The state-of-the-art TCXOs of analog type can produce a frequency stability of less than ±0.5ppm for the ambient temperature variation from -30℃ to 70℃[2]. The designed TCXO has a frequency deviation of less than ±2.5ppm.

The current conveyor is the basic building block for the current mode processing. In this paper, the NIC needed for oscillation is obtained by using the modified Fabre-Normand circuit[3].

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2 Temperature-Compensation Circuit

Generally, AT-cut crystal are used in crystal oscillators. The temperature characteristics of an AT-cut quartz crystal have been well approximated by the cubic function represented by the following equation.

$$\frac{\Delta f}{f} = A_1(t-t_o) + A_2(t-t_o)^2 + A_3(t-t_o)^3 \quad (1)$$

The coefficients A_1, A_2, and A_3 depend on physical properties of the crystal including the angle of the cut, ration of dimension, order of overtone, shape of plate, and type of mounting.

2.1 Desensitization circuit for the varactor

The equivalent circuit of the crystal is shown in Fig. 1 along with the load capacitance.

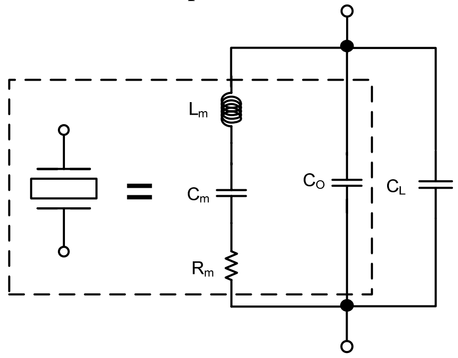

Fig. 1. Equivalent circuit of the crystal with the load capacitance

The load capacitance, C_L, and the crystal's electrode capacitance, C_O, are effectively in parallel, resulting in the parallel resonance frequency, f_L. f_L can be expressed as shown in equation (2).

$$f_L \cong \frac{1}{2\pi}\sqrt{\left(\frac{1}{L_m C_m}\right)}\sqrt{\left(1+\frac{C_m}{(C_O+C_L)}\right)} \qquad (2)$$

The equation (2) shows that f_L is changed by the load capacitance, C_L. If the temperature compensation circuit properly adjusts C_L, TCXO can be implemented. For example, the increase of C_L will shift the parallel resonance frequency down. The crystal used in this work has a ±10ppm frequency deviation for the temperature range from -30℃ to 70℃. The external load includes a varactor diode for variable capacitance. Equation (3) shows the required capacitance for temperature compensation.

$$C_{comp} = 2C_L - \frac{C_m}{2\left(\frac{\Delta f_L}{f_s}+\frac{C_m}{2(C_O+C_L)}\right)} + C_O \qquad (3)$$

Solving the equation (3), we can determine that the required load capacitance ranges from 20.66pF to 19.30pF. It is very inconvenient to use the varactor alone as the load capacitance, because the varactor capacitance changes too abruptly with the control voltage. So, the varactor is connected in series, as in Fig. 2 with a capacitor to desensitize the variation in the load capacitance.

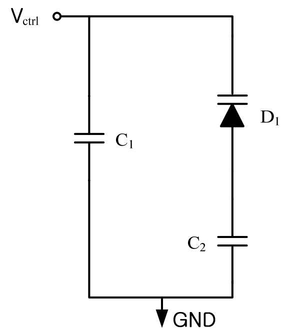

Fig. 2. Desensitization circuit for the varactor

Accounting for the effects of the C_1 and C_2, the required capacitance for the varactor diode is from 4.30pF to 5.66pF. Although the variation of capacitance equal 1.36pF, the control voltage changes from 0.55V to 2.3V. So, it is possible to compensate for the temperature range from -30℃ to 70℃. C_1 is 15pF and C_2 is 8pF in this work.

2.2 Thermistor network

Since the AT-cut crystal shows temperature characteristics of a cubic function, the entire temperature range can be divided into three sections. In the conventional analog TCXOs, the entire temperature range was divided into low and high temperature sections and the thermistor network used only NTC(Negative Temperature Coefficient) types. Since we want to cover the three sections, we would normally need to combine three voltage dividers. However, if a PTC(Positive Temperature Coefficient) thermistor is used, only two voltage dividers would suffice. The thermistors of both polarities are used in this work. Fig. 3 shows the entire thermistor network.

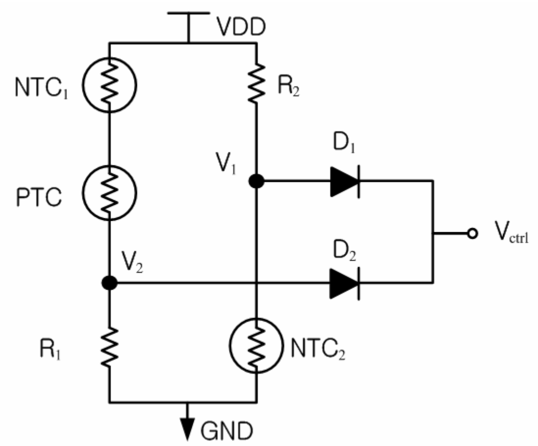

Fig. 3. Thermistor network circuit

The two sections of temperature compensation use diodes to combine the different regions of operation.

Temp (℃)	Frequency deviation(ppm)	Capacitance (pF)	Varactor diode's voltage(V)
-30	5	5.33	1.67
-20	9	5.60	1.32
-10	10	5.66	1.22
0	9	5.60	1.32
10	6	5.43	1.52
20	2	5.13	1.82
25	0	5	1.92
30	-2	4.86	2.22
40	-6	4.58	2.73
50	-9	4.37	2.82
55	-10	4.30	2.97
60	-10	4.30	2.97
70	-9	4.37	2.82
75	-7	4.51	2.7

Table 1. Required voltage of varactor diode

Table 1 shows the required capacitance and the control voltage to be applied to the varactor to obtain the needed capacitance.

3 Negative Impedance Converter Circuit

To increase the versatility of the current conveyor, a second version in which no current flows into terminal Y, was introduced in 1968[8]. Utilizing the same block diagram representation of Fig. 4, the CCII is described by equation (5)

$$V_x = V_y,\ i_y = 0,\ i_z = \pm i_x \quad (5)$$

Terminal Y exhibits an infinite input impedance. The voltage at X follows that applied to Y, thus X exhibits zero input impedance. The current supplied to X is conveyed to the high impedance output Z where it is supplied with either CCII+(positive polarity) or CCII-(negative polarity). The three-port behavior of the second generation current conveyor (positive or negative) can be depicted as shown in Fig. 4.

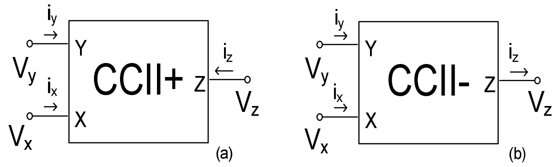

Fig. 4. CCII (a)positive polarity, (b)negative polarity

The modified Fabre-Normand circuit shown in Fig. 5 is used in this work.

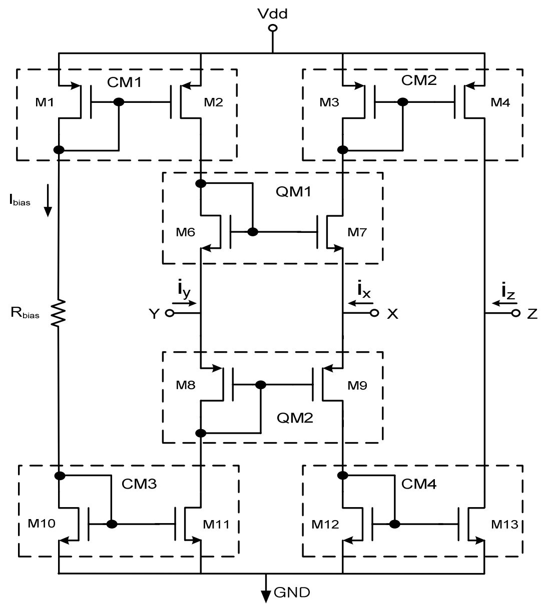

Fig. 5. Modified Fabre-Normand circuit

The original Fabre-Normand circuit consists of four current mirrors, a biasing resistor and a translinear cell composed of two current quasi-mirrors. If all the transistors are matched and have infinite output resistances, then transistors from M6 to M9 have equal gate-source voltages and currents. It fulfills the second condition in equation (5). Current quasi-mirrors from M6 to M9 form a translinear cell containing a closed loop

$$V_{gs6} - V_{gs7} - V_{gs8} + V_{gs9} = 0 \quad (6)$$

Because the transistors from M6 to M9 have equal gate -source voltages, the equation (7) is presented.

$$V_{gs6} = V_{gs7} = V_{gs8} = V_{gs9} \quad (7)$$

All transistors in the translinear cell have equal gate-source voltages, thus, $V_x = V_y$. The first condition in equation (5) is satisfied. Change of the currents i_{d7} and i_{d9} are equal i_{d4} and i_{d13} ,which are mirrored by the current mirrors CM2 and CM4, respectively. As a result of $i_x = i_z$, the last condition in equation (5) is also satisfied. Therefore the modified Fabre-Normand circuit is a CCII.

Current conveyors can be configured in such a way to perform the function of a negative impedance converter, which is useful for the implementation of the active part of an oscillator. After the terminal Y is connected to the terminal Z, the current through R is $i_z + i_y = i_z = i_x$, and $V_x = V_y$. So the input impedance is $R_{in} = V_x / (- i_x) = -R$. In this work, the terminal Y is connected to 1MΩ resistor and the terminal X is connected to the 16MHz crystal. The output is obtained from the terminal Z.

4 Simulation and Test

The designed TCXO oscillates at 16MHz as shown in Fig. 6. The TCXO has ±2.5ppm frequency deviation in the temperature range from -20℃ to 70℃. However the test data shows that the TCXO has ±4ppm frequency deviation as shown in Fig. 7.

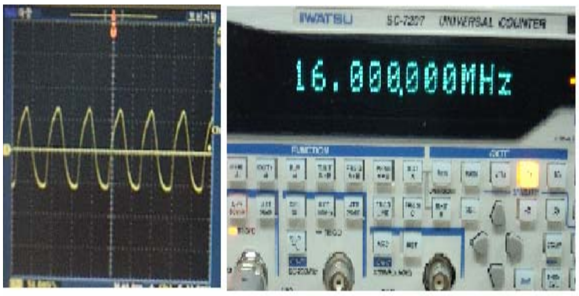

Fig. 6 Measured waveform and data of TCXO

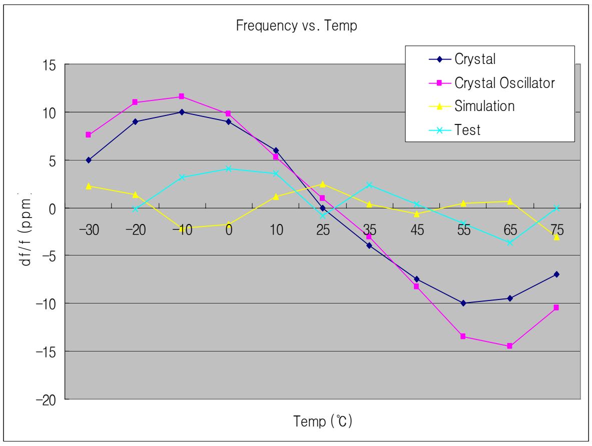

Fig. 7 Simulation vs. measurement

There are several reasons for the error between simulation and measurement. First of all, the accurate data for the varactor diode's capacitance as a function of the applied voltage were not available. Secondly, it was assumed that the frequency deviation of the crystal oscillator was entirely due to the temperature characteristics of the crystal itself. Thirdly, the temperature compensated circuit did not account for the exact shape of the temperature curve.

5 Conclusion

The designed TCXO oscillates at 16MHz and has ±4ppm frequency deviation for the temperature range from -20℃ to 70℃. The temperature compensation is done by a thermistor network consisting of both NTC-type and PTC-type thermistors, diodes, and resistors. The proposed thermistor network covers the whole temperature range described by a cubic function. The proposed TCXO was fabricated using the 0.25㎛ CMOS process and was tested to verify the temperature compensation.

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