The Design of Temperature-Compensated Surface Acoustic Wave Oscillator

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Abstract: - The design technique of a temperature-compensated SAW oscillator (TCSO) was thoroughly studied. The circuit of the TCSO contains two main parts, one is oscillation circuit and the other is temperature compensation circuit. In this work, the oscillator circuit adopted a commercial one-port SAW resonator at 433.92MHz in its resonant circuit. The reflection circuit model for oscillator design was applied. The performances of the designed TCSO are output power 10.6dBm, phase noise -138dBc/Hz at 10 KHz offset from carrier frequency, and maximum frequency deviation -40ppm from -10ºC to 85ºC.

Key-Words: - Oscillators, Surface Acoustic Wave Resonator, Temperature-Compensated Circuit.

1. Introduction
Surface acoustic wave (SAW) devices have the advantages of compact, superior performance, highly reproducible and reliable. Recently, owing to the improvement in design and fabrication techniques, SAW devices have been widely applied on the products of communication, computer and consumer electronics, such as RF and IF filters and oscillators [1]. Although SAW oscillator presents better phase noise and frequency stability than LC oscillator, the frequency stability with temperature changing is still a crucial issue for a high performance communication system. In this paper, a temperature-compensated SAW oscillator was designed and verified by experiment. This TCSO employed a one-port SAW resonator operated at 433.92MHz in its oscillation circuit and along with a temperature-compensated circuit.

2. Method for temperature compensation
The circuit of TCSO is divided into two parts, one is the voltage controlled SAW oscillator (VCSO) and the other is the temperature-compensation circuit as shown in figure 1. The VCSO includes an amplifier, a varactor diode and an one-port SAW resonator. As stated in many circuit design textbook [2-3], the oscillation frequency can be expressed as

\[
 f_o = \frac{1}{2\pi\sqrt{LC}} \quad (1)
\]

Where, \( L \) and \( C \) are equivalent capacitance and inductance of the resonant tank circuit, respectively. The varactor diode is eventually a PN diode operated in reverse bias. The junction capacitance of a varactor, considered as a parallel capacitor, can be calculated by \( C = kA/d \), where \( C \) is capacitance, \( A \) is the cross section area of the junction, \( d \) is the width of depletion region and \( k \) is a constant. The capacitance \( C \) is direct proportion of the area \( A \) and inverse proportion of the width \( d \). When the reverse voltage decreases, the depletion region of PN junction becomes narrower and the capacitance increases. On the contrary, the capacitance decreases as the reverse bias increases. The temperature compensation circuit senses the temperature variation and transfers to a bias voltage signal on varactor diode. By variation the junction capacitance of varactor diode, the frequency compensation can be achieved. Figure 2 depicts the principle of temperature compensation effect. In this figure, the horizontal axis represents the variation of temperature and the vertical axis shows the relation of compensation voltage and frequency of oscillation. Curve A is the oscillation frequency without the temperature compensation, curve B is compensation voltage applied on varactor diode, and curve C depicts the oscillation frequency after compensation.

![Fig.1 Block diagram of temperature-compensated SAW oscillator.](image-url)
3. Theorem of Oscillation

The reflection model was used to analyze the oscillator. Figure 3 shows the equivalent circuit model of the oscillator, where $Z_{in}$ is the impedance of active circuit and $Z_L$ is the load impedance of passive circuit. $a_m$ indicates a noise source. $a_m$ and $b_m$ represent the amplitude of incident and reflection voltage to and from $Z_{in}$, and $a_L$ and $b_L$ represent the amplitude of incident and reflection voltage to and from $Z_L$, respectively [3-6].

The reflection coefficients looking into source and load are defined as $\Gamma_{in} = \frac{b_m}{a_m}$ and $\Gamma_L = \frac{b_L}{a_L}$. From circuit analysis:

$$a_m = \frac{\Gamma_L a_m}{1 - \Gamma_L \Gamma_{in}}$$

(2)

The condition for oscillation is:

$$\Gamma_L \Gamma_{in} = 1$$

(3)

From the relationship of load impedance and reflection coefficient, equation (3) can be derived:

$$\Gamma_L \Gamma_{in} = \frac{Z_{in}Z_L - Z_0(Z_{in} + Z_L) + Z_0^2}{Z_{in}Z_L + Z_0(Z_{in} + Z_L) + Z_0^2} = 1$$

(4)

$$\begin{align*}
R_m + R_L &= 0 \\
X_m + X_L &= 0
\end{align*}$$

(5)

Since the load is a passive network, the real part of load impedance $R_L$ is positive. To satisfy the oscillation condition, the real part of active circuit $R_m$ should be a negative value which means the active circuit should provide enough energy to support a stable oscillation. The equation of imaginary part determines the frequency of oscillation that is oscillation can only occurs at the frequency where $X_L = -X_{in}$. Therefore, as illustrated by the diagram of reflection model of oscillator shown in figure 4, the criteria for initial oscillation are expressed in equations (6) and (7) [5].

$$\left| \frac{1}{S_{11}} \right| < 1$$

(6)

$$\angle \left( \frac{1}{S_{11}} \right) = \angle \Gamma$$

(7)

4. Design Example

Based the theory mentioned above, the designed oscillation and temperature compensation circuits are given in figures 5 and 6. In figure 5, $R_1$, $R_2$, $R_e$ and $R_l$ are for bias resistors; $C_3$ and $C_4$ are coupling capacitors for DC block. Shunt-feedback capacitors $C_1$ and $C_2$ are employed to guarantee the active circuit operate in unstable region ($S_{11} > 1$). An RF chock is placed to separate the RF signal and DC voltage. In figure 6, OP1 and OP2 work as voltage follower which use the nature character of operation amplifier that have a large input impedance to avoid loading effect on output voltage. The output voltage of OP1 $V_a$ is the reference voltage and the output voltage of OP2 $V_b$ is the voltage transferred from the temperature sensor AD590. OP3 is a differential amplifier that takes the voltage difference between $V_b$ and $V_a$. If $R_3 = R_2$ and $R_e = R_5$, the gain and the output voltage of OP3 are equal to $K = \frac{R_4}{R_3}$ and $V_c = \frac{R_e}{R_5}(V_b - V_a)$. OP4 works as voltage scalar that adds a reference voltage $V_d$ to the output voltage of OP3. By adjusting $K$ and $V_d$, the purpose of temperature compensation can be obtained.
The designed parameters of oscillation circuit are listed as follows:

1. Center frequency is 433.92MHz for SAW resonator.
2. Topology of the circuit: Colpitts oscillator.
3. Active device: NEC NE85633
4. DC bias: \( V_{ce} = 5V, I_c = 15mA \)
5. PCB substrate: FR4 substrate with dielectric thickness 1.6mm.

The simulation results of the oscillator are shown in figures 7 to 10, respectively. Figure 7 shows the criteria for initial oscillation where \( \left| \frac{1}{S_{11}} \right| < |\Gamma| \). Figure 8 shows the imaginary part of impedance is equal to zero at frequency 433.83MHz, and the real part of the impedance is negative. The power spectrum and the phase noise of the oscillator are given in figures 9 and 10 respectively.

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**Fig.5** The schematic diagram of oscillation circuit.

**Fig.6** The schematic diagram of temperature compensation circuit.

**Fig.7** Simulated the criteria of oscillator, \( \left| \frac{1}{S_{11}} \right| < |\Gamma| \) and \( \theta \left( \frac{1}{S_{11}} \right) = \angle \Gamma \).

**Fig.8** Simulated impedance performance, curve A is imaginary part and curve B is real part of impedance.

**Fig.9** Simulate power spectrum.
5. Experiment and Measurement

The realized TCSO hardware is shown in figure 11, and the measurement results are represented in figures 12 and 13. The frequency versus temperature from -40°C to 80°C of uncompensated oscillator is displayed in figure 14. The temperature characteristic of uncompensated oscillator is a parabolic curve with turnover temperature near 20 ºC. In order to compensate the frequency from -40°C~80°C, two compensated circuits were needed, one for below 0°C and the other one for above 0°C. All the measurements are done with a frequency counter in an environmentally controlled chamber (temperature range and tolerance: -40°C to 100°C and ±0.2°C, humidity range and tolerance: 10% to 98%RH and ±2%). The oscillation frequencies are recorded on 10°C per step. The temperature characteristics of compensated oscillator are shown in figures 15 and figure 16. From the measurement results, the maximum frequency deviation above 0°C is improved from 136ppm to 40ppm.
6. Conclusions

In this paper, a temperature-compensated SAW oscillator was designed successfully. The reflection oscillator model was employed to design a high output power and low phase noise SAW oscillator. The oscillator frequency is 433.85 MHz, output power is 10.6dBm and -138dBc/Hz phase noise at 10 KHz offset from carrier frequency. The temperature compensation circuit using temperature sensor IC AD590 improved the frequency deviation from 136ppm to 40ppm.

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