

Design and Study of Temperature Compensated Crystal Oscillator Based on Low Phase Noise

Linliang Wang^{1,*}

¹Taiwan Crystal (Ningbo) Electronics Co. Ningbo, Zhejiang, 315000, China

*Corresponding author: Linliang Wang (Email: 12229856@qq.com)

Abstract

In this paper, a temperature-compensated crystal oscillator (TCXO) design scheme based on low phase noise is proposed to address the problems of poor frequency stability and high phase noise of crystal oscillators under temperature change. By analyzing Leeson's phase noise model and the frequency-temperature characteristics of the crystal, the phase noise is reduced by optimizing the structure of the oscillator circuit, choosing a high-Q crystal resonator, selecting low-noise devices, and suppressing the power supply noise; at the same time, combining with the digital and analog hybrid compensation technology, the temperature sensor, polynomial voltage function generator and varactor diode are used to achieve accurate temperature compensation. The experimental results show that the designed TCXO has a phase noise of -160dBc/Hz at 10kHz offset and a temperature stability of $\pm 0.5\text{ppm}$ ($-40^{\circ}\text{C} \sim 85^{\circ}\text{C}$), and the long-term reliability is verified by aging test. This study provides theoretical support and practical reference for the design and optimization of high-precision and low-noise crystal oscillators.

Keywords

Temperature-compensated crystal oscillator; Low phase noise; Circuit design.

1. INTRODUCTION

As the core frequency source of modern communication and electronic systems, the frequency stability and phase noise performance of crystal oscillators directly affect system accuracy and reliability [1]. However, traditional crystal oscillators are susceptible to temperature drift, and device noise in the circuit can deteriorate the phase noise index. Although existing temperature compensation techniques can partially alleviate the temperature drift problem, there are still limitations such as insufficient compensation accuracy and slow dynamic response. In addition, the reduction of phase noise needs to be optimized by considering multiple factors such as circuit design, device selection and noise suppression [2]. To this end, this paper proposes a new type of low phase noise temperature compensated crystal oscillator design scheme, through theoretical modeling, circuit structure innovation and hybrid compensation strategy, to achieve the dual objectives of high frequency stability and low phase noise. The research not only improves the theoretical system of TCXO design, but also provides a technical path for the miniaturization and intelligence of high-precision time-frequency devices.

2. THEORETICAL FOUNDATION

2.1. Mechanism and theoretical modeling of phase noise generation

Phase noise is the instantaneous frequency or phase fluctuation triggered by various random noises, which reflects the short-term stability of the oscillator output frequency. In crystal oscillator circuits, components such as resistors, capacitors, inductors, diodes, transistors, etc. generate internal noise, with transistors having the most significant noise impact.

According to the Leeson model, the single sideband phase noise of the oscillator can be expressed as [3]:

$$\frac{1}{8} \frac{FkT}{P_{ai}} \left(\frac{f_0}{f_m} \right)^2 \left(\frac{P_i}{\omega_0 W_c} + \frac{1}{Q_{UL}} + \frac{P_0}{\omega_0 W_c} \right) \left(1 + \frac{f_c}{f_m} \right)$$

Where, $\omega_0 W_c$ is the reactance power, ω_0 is the resonant frequency, P_0 is the output signal power, P_i is the feedback input signal power, P_{ai} is the main oscillator signal output power, f_0 is the carrier frequency, f_m is the off-carrier frequency, F is the main oscillator noise coefficient, k is the Boltzmann's constant, T is the absolute temperature, Q_{UL} is the resonance circuit quality factor, f_c is the corner frequency. From this model, it can be seen that reducing the output phase noise of the crystal oscillator can be done from several aspects, such as increasing the output signal power of the main oscillator circuit, selecting active devices with low noise index, reducing the noise of the passive network, and upgrading the quality factor of the resonator.

2.2. Temperature compensation principle

The frequency of a crystal resonator changes with temperature, and its frequency-temperature characteristics can be approximated as a fifth power function [4]:

$$\frac{\Delta f}{f} = A_5(T - T_0)^5 + A_4(T - T_0)^4 + A_3(T - T_0)^3 + A_2(T - T_0)^2 + A_1(T - T_0)^1 + A_0$$

Where, f is the crystal resonant frequency, Δf is the frequency variation, $A_1 - A_5$ is the coefficient of each term, A_0 is the constant term, T is the temperature, and T_0 is the center temperature. The core principle of temperature compensation is to adjust the frequency of the voltage-controlled oscillator by generating a temperature-dependent compensation voltage to offset the change in the crystal's own frequency with temperature. For example, when the crystal frequency decreases due to an increase in temperature, the compensation circuit generates a corresponding voltage to increase the frequency of the voltage-controlled oscillator, thus achieving frequency stabilization.

3. SYSTEM DESIGN AND IMPLEMENTATION

3.1. Key techniques for low phase noise design

(1) Optimization of oscillating circuit design: choosing a suitable form of oscillating circuit is the key to achieving low phase noise [5]. For example, the improved Butler oscillation circuit effectively reduces the phase noise of the output signal by optimizing the circuit parameters and structure. At the same time, the reasonable design of the feedback network and frequency selection network of the oscillation circuit can improve the stability and frequency selection performance of the circuit and further reduce the phase noise

(2) Selection of high-quality crystal resonators: According to the design requirements, select crystal resonators with high crystal resonator quality factor (Q value) and low aging rate [6]. For example, the SC cut 5 times overtone high Q crystal resonator, its superior performance can effectively improve the phase noise index and frequency stability of the oscillator.

(3) Application of low-noise active devices: active devices with low noise figure and low flicker noise are carefully selected, and their static operating point is precisely set to ensure that the amplifier operates in the best state and to reduce the introduction of phase modulation noise. Meanwhile, in the circuit design, the active devices are reasonably laid out to avoid mutual interference and further reduce the noise.

(4) Power supply noise suppression technology: using low noise linear regulator and efficient filtering circuit, the power supply is strictly stabilized and filtered to reduce the impact of power supply ripple and noise on the oscillator circuit. In PCB wiring, reasonable planning of power supply alignment to reduce the coupling path of power supply noise and improve the anti-interference ability of the oscillator.

3.2. Overall design program analysis

3.2.1 Circuit design details

(1) Oscillation circuit design: the oscillation circuit adopts the Colpitts oscillation circuit, which has a simple structure, high reliability and good frequency selection characteristics [7]. The crystal resonator is used as the resonant element and narrow-band filter of the circuit, which effectively improves the on-load Q of the circuit and reduces the static phase noise. In the circuit design, active devices with low flicker noise are selected and their static operating point and excitation level are reasonably set to further optimize the phase noise performance.

(2) Temperature Compensation Circuit Design: The temperature compensation circuit is mainly composed of a temperature sensor, a 5-fold voltage function generator and an adder, etc. The temperature sensor is based on the temperature characteristics of semiconductor P-N junction. The temperature sensor is based on the semiconductor P-N junction temperature characteristics of the sensor, the temperature information will be accurately converted into voltage information. 5 times the voltage function generator according to the frequency-temperature characteristics of the crystal resonator, the output voltage of the temperature sensor is converted into 5 times the compensation voltage. An adder adds the compensation voltage to the reference voltage to obtain the final voltage-controlled compensation voltage, realizing high-precision temperature compensation.

(3) Voltage regulator circuit design: The voltage regulator circuit adopts a low-noise linear regulator and combines an operational amplifier with large power supply ripple suppression and low noise characteristics as the power supply unit. Reasonable filter capacitors are set at the output side, which effectively reduces the impact of power supply voltage changes on the performance of the crystal oscillator, significantly reduces the power supply noise, and improves the near-end phase noise index of the oscillator.

(3) Amplifier circuit design: The amplifier circuit adopts a low-noise logic non-gate to buffer the amplified output, and adds a type matching network at the back end. This design not only meets the spectral purity requirements of the output signal, but also ensures impedance matching, which can adapt to different load conditions and enhance the adaptability of the oscillator in different application scenarios.

3.2.2 Device Selection Strategy

(1) Crystal Resonator Selection: Considering the cut type, Q value, overtone number, inflection point, frequency difference, equivalent resistance, static capacitance and other parameters, the SC cut 5 times overtone high Q crystal resonator is selected. The crystal resonator has the advantages of small frequency temperature coefficient, high short-term frequency stability, low aging rate, etc., which can effectively improve the phase noise and frequency stability index of the oscillator.

(2) Transistor selection: focus on the noise figure, taking into account the requirements of low temperature drift, high gain and small package. Selecting transistors with low noise figure

can reduce the noise introduced by the amplifier and improve the overall performance of the oscillator [8]. At the same time, the temperature drift characteristics and gain characteristics of the transistor are considered to ensure the stable operation of the oscillator in different temperature environments.

(3) Other device selection: For other devices such as resistors, capacitors, inductors, etc., low noise types are selected. Under the premise of ensuring electrical performance, try to reduce the noise of the device itself to reduce the interference with the oscillation circuit, so as to achieve the design goal of low phase noise.

3.3. System Design Options

3.3.1 Crystal selection and characterization

(1) High Q Crystals: Choose AT-cut or SC-cut crystals for their excellent temperature stability and high Q, which helps reduce phase noise.

(2) Temperature Characterization Test: Measurement of the crystal frequency versus temperature curve (typically a cubic polynomial) to provide data support for compensation algorithms.

(3) Resonance Mode: Prefer fundamental frequency mode over overtone mode to reduce circuit complexity and parasitic effects.

3.3.2 Oscillator circuit design

(1) Topology selection: a modified Pierce oscillator or Clapper oscillator is used to optimize phase noise performance.

(2) Clapper structure: isolates the crystal from the transistor by a series capacitor to reduce the effect of device noise on the Q value.

(3) Low Noise Devices: Transistors are selected from low noise BJTs or FETs (e.g. GaAsFETs), the operating point is set in the low noise region, and high stability, low temperature drift capacitors and resistors are used.

(4) Load Capacitance Matching: Precise calculation of load capacitance (CL1 and CL2) ensures that the crystal resonates at the target frequency.

3.3.3 Temperature compensation circuit design

Temperature sensor: Integrate a high-precision digital sensor (e.g., PTAT circuit or MEMS sensor) mounted close to the crystal to monitor temperature in real time.

(2) Compensation element: Use a low leakage current varactor diode (e.g., superabrupt junction varactor) with a capacitance range that covers the temperature drift of the crystal frequency.

(3) Compensation algorithm:

Digital compensation: the microcontroller reads the temperature data and generates the compensation voltage (DAC output drives the varactor) through table lookup or polynomial fitting.

Analog compensation: the thermistor network directly generates the compensation voltage, which is suitable for fast response but low precision scenarios.

(4) Linearization: Segmented linear compensation of the capacitance-voltage (C-V) curve of the varactor diode to avoid nonlinear error.

3.3.4 Phase noise optimization measures

(1) Power supply noise suppression: Low-noise LDOs (e.g., TPS7A series) are used to independently supply power to the oscillator circuit. Power path additive filter (10 μ F tantalum capacitor + magnetic bead + 0.1 μ F ceramic capacitor).

(2) Grounding and Layout: Split analog/digital ground, single point connection to reduce return interference. Shorten the high-frequency signal alignment to avoid cross-interference; lay ground shielding under the crystal.

(3) Loop gain optimization: Adjust the feedback resistor (e.g., 1M Ω) and limiter circuit (back-to-back diode) to avoid overdriving resulting in Q degradation.

3.3.5 Prototype Testing and Calibration

(1) Phase Noise Test: Measure phase noise at 10 Hz to 1 MHz offset using a signal source analyzer (e.g., Keysight E5052B) optimized to -160 dBc/Hz@10 kHz (typical 10 MHz TCXO).

(2) Temperature cycling test: Verify frequency stability over the range of -40°C to 85°C (target ± 0.5 ppm), record actual compensation error, and iteratively update compensation coefficients.

(3) Aging test: Long-term operation to evaluate frequency drift and incorporate aging compensation algorithms if necessary.

3.3.6 Advanced Optimization Directions

(1) Hybrid Compensation Technology: Combining the fast response of analog circuits with the high accuracy of digital circuits to improve dynamic temperature compensation performance.

(2) MEMS TCXO: Explore the integration of silicon-based microelectromechanical systems (MEMS) with crystals to reduce size and improve vibration resistance.

(3) AI-assisted calibration: Use machine learning algorithms to automatically optimize compensation parameters and shorten development cycles.

4. CONCLUSION

In this study, the theoretical direction of the design is clarified through an in-depth analysis of the phase noise generation mechanism and temperature compensation principle. In terms of low phase noise design, the phase noise is effectively reduced by adopting key techniques such as optimizing the oscillation circuit design, selecting high-quality crystal resonators and low-noise active devices, and suppressing power supply noise. In the overall design scheme, a comprehensive planning is carried out from the circuit design details to the device selection strategy. The reasonable design of the oscillation circuit, temperature compensation circuit, voltage regulator circuit and amplifier circuit, as well as the proper selection of various types of devices, provide a guarantee for the realization of high-performance oscillator. The system design scheme covers crystal selection, oscillation circuit optimization, temperature compensation algorithm, phase noise suppression, prototype testing and calibration, etc., which ensures the stability and reliability of the oscillator under different operating conditions. The validity of the design is verified through prototype testing and calibration, and data support is provided for subsequent improvement. Meanwhile, the proposed hybrid compensation technique, MEMS TCXO integration, and AI-assisted calibration and other advanced optimization directions point out the research direction for further improving the performance of temperature-compensated crystal oscillators in the future.

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