An Improved Microcontroller Compensated Low Phase Noise Overtone TCXO

Wei Fu, Xianhe Huang, Feng Tan, Peng Dai, Yan Wang
University of Electronic Science and Technology of China
Chengdu, Sichuan, China
xianhehuang@uestc.edu.cn

Abstract **- This paper presented an improved design on a 121.4MHz overtone TCXO which exhibited a low phase noise. The temperature compensation approach differs from conventional ones such as adding series inductances or frequency multiplication. It makes of a 100MHz 5th overtone crystal oscillator mixed with the frequency of a 21.4MHz fundamental mode voltage controlled crystal oscillator (VCXO). And then, the mixed frequency was filtered and amplified to produce a 121.4MHz output. For a better performance, computer simulation tool as Agilent ADS was used to estimate the phase noise while designing these two oscillators. In this design, a microcontroller was used to control the compensating voltage of 21.4MHz VCXO at every appointed temperature to generate a frequency correction $\Delta f_t=\Delta f_{100}+\Delta f_{21.4}$ and to implement the total compensation. Experimental results show that the frequency-temperature stability of the prototype 121.4MHz TCXO has achieved $\pm 2\times 10^{-7}$ within the temperature range from -40 to 85℃. Besides, a phase noise level of -85dBc/Hz and -145dBc/Hz at 10Hz and 1 kHz offset has been realized.**

I. Introduction

With low power consumption, small size and good start-up characteristic, temperature-compensated crystal oscillators, especially ones with the working frequency more than 100 MHz, are universally used in the modern communication and electronic system. It greatly interests circuit designers as it can reduce frequency multiplication to improve the performance of a system.

The series-parallel resonance frequency interval of a crystal resonator is inversely proportional to the square of the overtone order. Thus, it is difficult to compensate on overtone crystal oscillator. Many investigations were made to implement high-frequency overtone TCXO [1]. At present, main engineering solutions are two as follows.

1) After compensating a fundamental frequency or low-order overtone oscillator, the output frequency is multiplied for high frequency use;

2) Directly compensating the output frequency of a high-order overtone crystal oscillator, where series inductances are added to crystal to widen the series-parallel resonant frequency interval.

Method *1)* would deteriorate phase noise with 20lgN slope. N is the multiplication times. Method *2)* has limitations either. Firstly, it makes the loaded Q factor of crystal lower and deteriorates the phase noise. Secondly, the temperature stability of crystal could be degraded because of the bad temperature characteristics of the inductance. The loaded Q factor can be proved by (1).

$$Q_L \approx \frac{Q_0}{1+\dfrac{R_t}{R\left(1-\omega^2 L_t C_0\right)^2}} \qquad (1)$$

Where:

Q_0 is the unloaded Q of crystal,
R_t is the loss resistance of the series inductance L_t,
R is the equivalent resistence of crystal,
ω is the series resonant frequency of crystal，
L_t is the series inductance,
C_0 is the shunt capacity across crystal.

Studies in past ten years indicate the design of frequency synthesis with the direct digital synthesizer (DDS) and the phase locked loop (PLL) can achieve temperature compensation with a high stability, and cover a wider range of the compensated frequency. Using this technique with the SC-cut dual-mode crystal oscillator as the temperature sensor, it achieves a specification of $\pm 2.5\times 10^{-8}$ from -40℃ to +85℃. If the AT-cut fundamental frequency crystal oscillator is used, it achieves $\pm(1\sim 3)\times 10^{-7}$ over the same temperature range[1]~[3]. But complex circuits exists in this method, and it is not suitable for universal use. Besides, the disadvantages of the PLL application are as follow [4].

1) The whole system is relatively complicated;

2) PLL contributes "technical noise" and a spur on comparison frequency;

3) The value of output frequency should belong to a frequency grid;

4) Phase noise is limited by noise floor of DDS and PLL.

In this study, a method based on frequency mixing was presented[5][6][7], and the sum frequency is picked out to get the stable 121.4 MHz signal. In this system, 21.4 MHz VCXO is used to directly compensate the total frequency deviation due to the temperature variation. Compared with [1] ~ [3], this method is much more simple and applicable in wide frequency range application.

978-1-4244-3510-4/09/$25.00 ©2009 IEEE

II. BASIC SCHEME OF 121.4MHZ TCXO

The system is composed of a 100 MHz 5th overtone crystal oscillator, a 21.4 MHz VCXO, a temperature sensor, a mixer, an A/D convertor, a D/A convertor, a microcontroller, an LC bandpass filter and a low noise amplifier[5][6][7] (block diagram shown in Fig. 1).

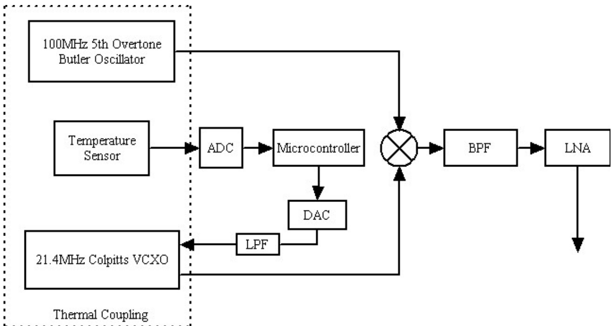

Fig.1. *Functional block diagram of 121.4MHz overtone TCXO*

The 100 MHz 5th overtone crystal oscillator is a Butler circuit, and the 21.4 MHz VCXO is a fundamental frequency voltage control crystal oscillator based on Colpitts circuit. The microcontroller STC12C4052AD is chosen to control the tuning voltage across varactor to tune the output frequency of the VCXO. Its operating temperature range is -40~+85℃. Using STC12C4052AD is quite convenient in downloading programs because of its ISP function [8]. The temperature sensor using DS18B20,which measure temperature range is -55~+125℃. The two oscillators and temperature sensor are bound together for good thermal coupling to minimize the thermal hysteresis effect [9]. STC12C4052AD calculate the digital value of the tuning voltage according to experimental temperature and frequency information. Then D/A convertor transform this digital value into the corresponding analog voltage to tune the 21.4 MHz VCXO. The lowpass filter here is used to smooth the tuning voltage and improve the noise. The output frequency of the 100 MHz overtone crystal oscillator is mixed with that of the VCXO. The spurious frequency component of mixed products is removed by the LC bandpass filter. Consequently, the stable signal is amplified and output.

III. SOME PRACTICAL CONSIDERATIONS ON CIRCUIT DESIGN AND SIMULATION

In the study, we found the phase noise of TCXO is mainly determined by that of the 100MHz low phase noise oscillator, the 21.4MHz VCXO, the mixer and the digital system. The main means to minimize these influences on a spectrum of the output signal as follows:

1) 100MHz low phase noise oscillator: It is based on Butler circuit. At above 20 MHz, the Butler common base circuit has many advantages than others. It can reach high frequency and has low noise. A simulation made by Agilent ADS to estimate its phase noise performance. The first stage circuit of the 100MHz Butler Oscillator is shown in Fig.2 and the simulation result is shown in Fig.3.

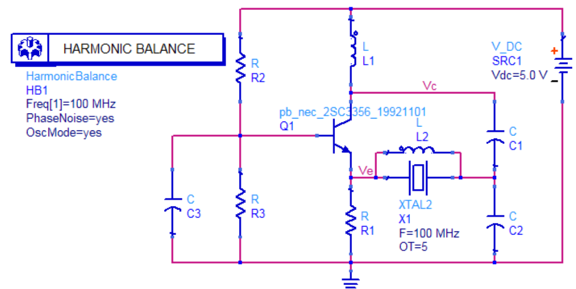

Fig.2. *The simulation circuit of first stage in the 100MHz Butler XO*

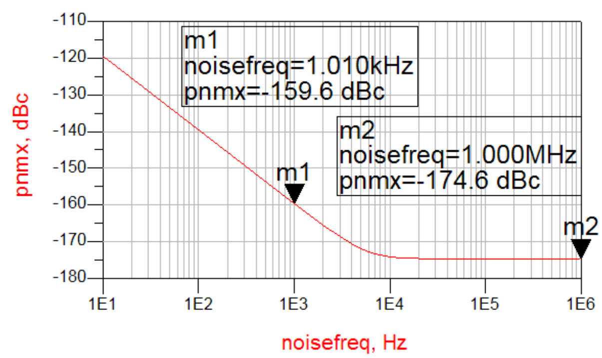

Fig.3. *The phase noise simulation result of the 100MHz XO*

2) 21.4MHz VCXO: It is firstly required a wide tuning frequency range. Since we know if frequency range which to be compensated is too large， the loaded Q-factor of resonator would be lower and so that of the oscillator, we use the Colpitts as a compromise between excellent phase noise performance and wide tuning frequency range.

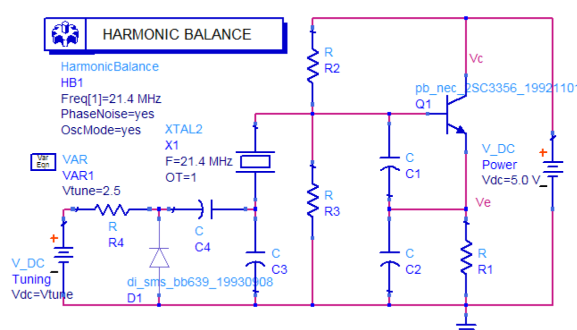

Fig.4. *The simulation circuit of 21.4MHz Colpitts VCXO*

We also simulated this Colpitts circuit shown in Fig.4 and the simulation result is shown in Fig.5.

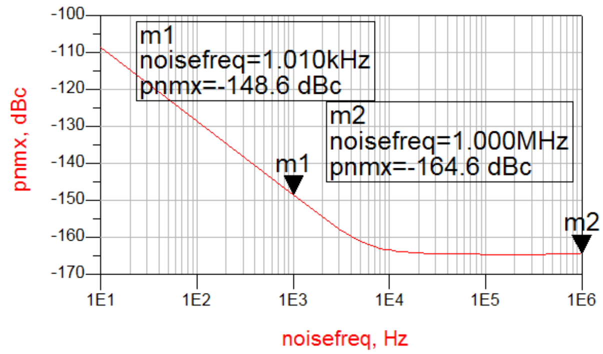

Fig.5. *The phase noise simulation result of 21.4MHz VCXO*

3) Low noise mixer: Commercial mixers can work at a wide frequency range, but the impedance matching is difficult, this deteriorates the phase noise. According to the experietial formula,the output noise of mixer should be like this:

$$N_o = kTBFG \tag{2}$$

Where T is absolute temperature, K is the Boltzmann's constant, B is the bandwidth of mixer, G is the gain of mixer. We designed a passive diodes mixer.

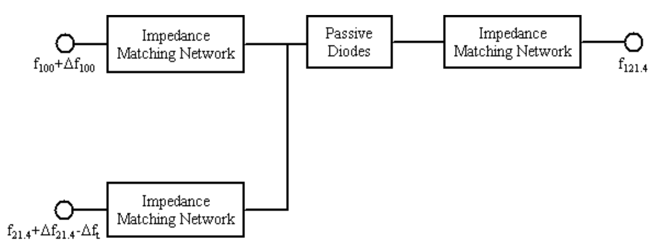

Fig.6. *Passive diode mixer diagram*

The mixer diagram is shown in Fig. 6. In this design, we compress its working frequency range and improve impedance matching to enhance its phase noise performance.

4) Digital system: A 10-bit D/A convertor is used in this system to convert the digit control output of MCU to analog compensating voltage. Besides, a passive low-pass filter is used to strongly decrease the fast frequency variations resulting from the real-time digital temperature sampling and compensation control signal to improve the noise in TCXO. The passive low pass filter with a time constant of about 0.4 second to produce a smooth function of compensation voltage without discrete voltage steps of D/A. As we known, there are fast frequency variations caused by the fast digital variations [10][11].

IV. Compensating Process And Result

Frequencies of 100 MHz overtone crystal oscillator and 21.4 MHz VCXO vary with the environment temperature. The total frequency-temperature characteristic curve is shown in Fig. 7.

Because the operating temperature of the microcontroller is -40~+85℃, we choose this range as compensation temperature range in experiment for a good performance. In this system, the tuning voltage ΔV can be generated by the microcontroller and then converted by a DAC. Continuous voltage values between every two measured voltages are calculated by the piecewise linear interpolation method [12]. The fitting results of compensating voltages are shown in Fig. 8 as a fitting curve. The central frequency f_0=121,375,500 Hz because the 21.4MHz resonator we used is only 21.375MHz.

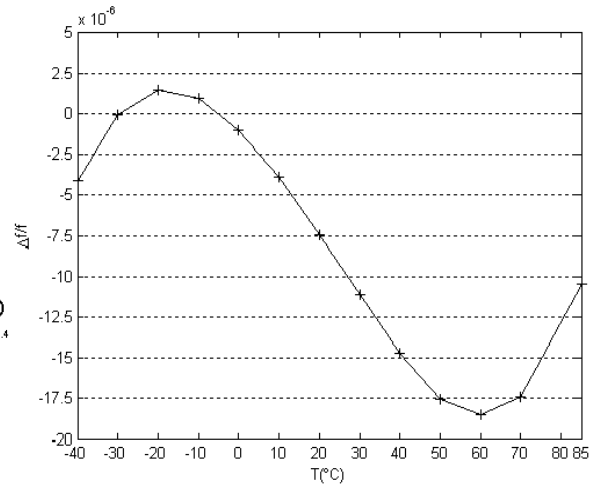

Fig.7. *The frequecny-temperature character of the system before compensation (the central frequency f_0=121,375,500Hz)*

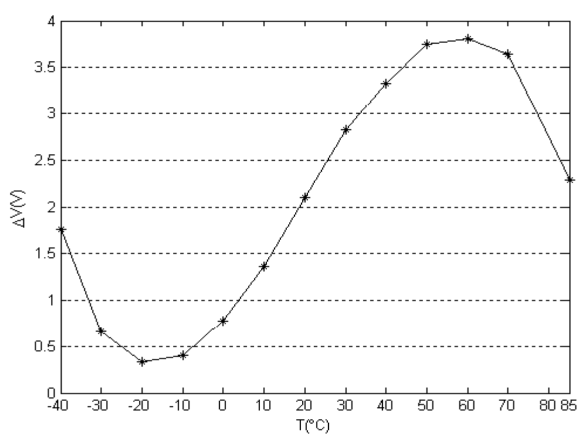

Fig.8. *Compensating voltage vs temperature of TCXO*

These voltages shown in Fig. 8 were programmed and download into the microcontroller. When temperature varies, the MCU control the tuning voltage values according to interpolation program, and then the tuning voltage is output so that the 121.4MHz overtone TCXO is compensated at the given temperature. Experimental results were shown in Fig. 9, the stability of this 121.4 MHz TCXO achieves $\pm 2\times 10^{-7}$ from -40℃ to +85℃.

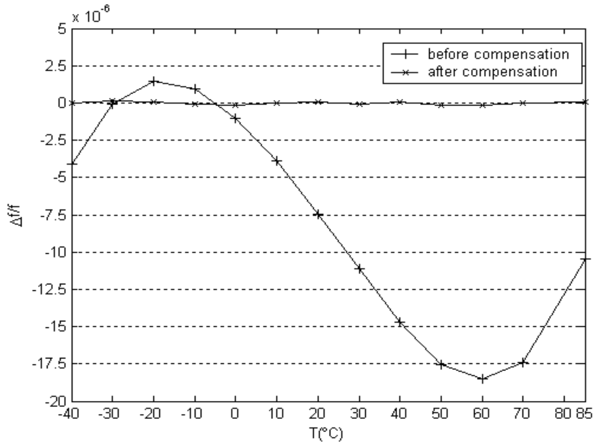

Fig.9. *Compensation result for the 121.4MHz overtone TCXO(central frequency f_0=121,375,500Hz)*

Besides, a phase noise of -85dBc/Hz and -145 dBc/Hz at 10Hz and 1kHz offset respectively is measured on the prototype TCXO with Agilent E5052B. The measured result is shown in Fig.10.

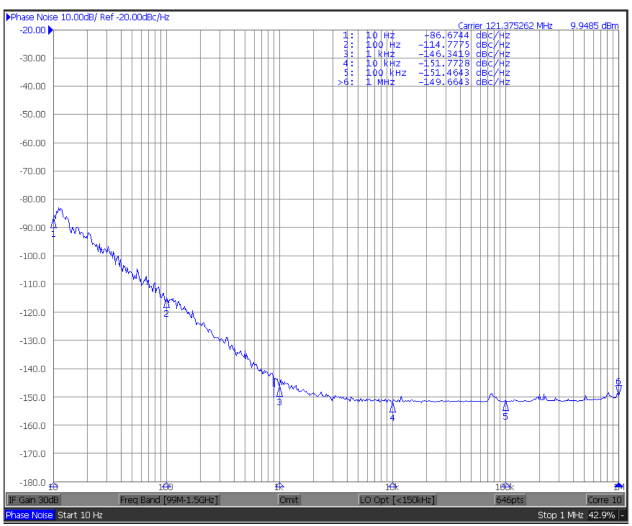

Fig.10. *Measured phase noise curve of the 121.4MHz TCXO*

Seen from experimental results above, to achieve the similar compensation stability of AT-cut fundamental frequency TCXO as [3], the 121.4 MHz high-frequency overtone TCXO presented in this paper is even more easily to implement.

V. CONCLUSION

A design of a 121.4 MHz overtone crystal oscillator with microcontroller temperature compensation was presented in this paper. The frequency-temperature stability of compensated 121.4MHz overtone TCXO achieves $\pm 2\times 10^{-7}$ over the temperature range from -40℃ to +85℃.

The phase noise of the prototype is measured -145dBc at 1KHz offset. This result is quite close to that of the computer simulation. Thus, the simulation gives a moderate result on estimating the phase noise characteristic except the noise floor is not good enough as the simulation predicted. Prominent advantages of this design are as follows:

1) It is helpful for implementing a high-frequency overtone TCXO conveniently with a relatively high stability.

2) It has potential to improve its performance on phase noise with this approach, and this is still in studying.

3) It is available for wider frequency range.

REFERENCES

[1] Frerking ,M. E. “Fifty years of progress in quartz crystal frequency standards,” in *Proc. IEEE Int. Freq. Contr. Symp.*,1996, pp. 33-46.

[2] Jackson, E, Phillips, H, Rose, B. E, “The microcomputer compensated crystal oscillator a progress report,” in *Proc. IEEE Int. Freq. Contr. Symp.*,1996, pp. 687-692.

[3] Rose, B. E, Phillips, H, “Development status of the microcomputer compensated crystal oscillator,” European frequency and time forum,1996,pp.190-195.

[4] Bogomolov, D.V.; Boroditsky, R.; “Low phase noise UHF TCXO,” Frequency Control Symposium and Exposition, of the 2005 IEEE International, pp. 509-511.

[5] X.-H. Huang, M.-Q. Li, W. Fu, and F. Tan, “A temperature compensating method for crystal oscillator”, Chinese Invention Patent ZL200410022680.3.

[6] MinQiang Li, XianHe Huang, Feng Tan, etc. “A novel microcomputer temperature-compensating method for an overtone crystal oscillator”, *IEEE Tran. Ultrason., Ferroelec., Fre. Contr.*, Vol.52, No.11, Nov,2005.

[7] Xianhe Huang, Wei Wei, Feng Tan, Wei Fu, “High-frequency Overtone TCXO Based on Mixing of Dual Crystal Oscillators”, *IEEE Tran. Ultrason., Ferroelec., Fre. Contr.,* Vol.54, No.6, June 2007.

[8] “STC12C4052AD User’s Manual”, Shenzhen Hongjing Electronics,Inc., China, 2003

[9] Anatoly V. Kosykh, Boris P. Ionov, “Temperature dynamic model and temperature dynamic compensation of crystal oscillators”, in *Proc. IEEE Int. Freq. Contr. Symp.*,1992, pp. 425-433.

[10] Eric Jacqet, Jean-pierre Bardon, Olivier Bignon; “Digitally compensated TCXO with low phase noise characteristics”, Joint Meeting EFTF-IEEE IFCS,1999.pp.370-375.

[11] Buroker,G.E.; Frerking,M.E.; “A digitally compensated TCXO”, 27th Annual Symposium on Frequency Control, 1973,pp. 191–198

[12] A. Kosykh, V. Bagaev, B. Ionov, A. Lepetaev, S. Zavialov, “The new method of statistic piecewise-linear interpolation and its application to DTCXO creation”, in *Proc. IEEE Int. Freq. Contr. Symp.*,1993, pp. 687-697.