Biomedical Research 2018; Special Issue: S402-S405

ISSN 0970-938X
www.biomedres.info

The analysis and design of a 50MHz Colpitts low phase noise crystal oscillator.

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Abstract

Crystal oscillators have huge demand in medical filed especially in building medical devices. They are used in diagnostic equipment, monitoring devices, hearing aids, etc. Since they are widely used in medical devices, it is essential to maintain accurate requirements for the output phase noise of reference frequency source. At the same time it is important to find out new ways to reduce the phase noise which is the major problem in designing crystal oscillators. The importance of loaded quality factor Q_L is analyzed on the basis of Leeson model and the formula of Q_L is derived from the analysis of Colpitts oscillator circuit. According to the results, we can draw a conclusion that Q_L is explicitly related to circuit parameters. The phase noise of the 50MHz Colpitts crystal oscillator is simulated by the Agilent Advanced Design System (ADS). Based on the simulation results, a design of the prototype crystal oscillator is presented. The crystal resonator we use is AT-cut 3rd overtone crystal resonator with 49 U resistance welding package, its unloaded quality factor Q_0 is about 1.45×10^5. The measured results of phase noise are -107 dBc/Hz@10Hz, -134 dBc/Hz@100Hz and -152 dBc/Hz@1KHz. Experimental results show that it is feasible to design low phase noise crystal oscillators on the basis of improving Q_L.

Keywords: Leeson model, Loaded quality factor, Phase noise, Colpitts crystal oscillator.

Accepted on August 30, 2017

Introduction

With the development of modern communication technology, the requirement of the high stable crystal oscillator has increased. Crystal oscillators have numerous applications and they are widely used in medical devices such as defibrillators, neuro-stimulators, hearing aids, pacemakers, etc. [1]. They are also used in ultrasound, MRI equipment, wireless telemetry and diagnostic imaging. Neurologists often use oscillators for treating neurological disorders such as Parkinson's Disease through deep brain stimulation (DBS) [2,3]. Functional pacemakers coordinating circadian rhythms are constructed by coupling multiple oscillators. Circadian oscillators constitute positive and negative elements which can form autoregulatory feedback loops. These loops are used to generate 24-hour timing circuits [4,5]. Patients with middle ear dysfunction use Bone Anchored Hearing Aids which contains bone oscillators [6]. In many systems such as the medical field, satellite communication and radar system, there are very strict accuracy requirements for the output phase noise of reference frequency source. Therefore, the study of ways to reduce the phase noise is the primary problem in the process of design crystal oscillators [7-9].

In practical design, the phase noise is closely related to Q_L. By the analysis of Leeson formula derived from the phase noise model of Leeson, we can draw a conclusion that phase noise improves with the loaded quality factor Q_L increasing. The Leeson formula is as follows [10-13]:

$$S_{\Delta\phi}(f_m) = [1 + \frac{1}{f_m^2}(\frac{f_0}{2Q_L})^2]S_{\Delta\theta}(f_m) \rightarrow (1)$$

Where f_m is offset frequency, f_0 is center frequency, Q_L is loaded quality factor, $S_{\Delta\phi}(f_m)$ is the power spectral density of the output phase noise, $S_{\Delta\phi}(f_m)$ is the spectral density of the oscillator input phase noise. So a high Q_L is beneficial to reducing phase noise.

In this paper, the formula of Q_L is derived by the analysis of Colpitts oscillator circuit and we can obtain the relation between Q_L and circuit parameters. An appropriate increase in the value of capacitance C_2 can improve Q_L, thereby reduce the phase noise. According to the simulation results of 50 MHz Colpitts crystal oscillator using Agilent Advanced Design System (ADS), a design of the prototype crystal oscillator is presented and the measurement results of phase noise are reduced by adjusting the value of C_2.

The phase noise analysis of colpitts crystal oscillator

From the viewpoint of oscillator power spectrum, for BJT oscillator, the Q_L factor of a conventional two-port network is defined as [14-16]:

$$Q_L = \frac{\omega}{2}\left|\frac{1}{z(\omega)} \times \frac{dz(\omega)}{d\omega}\right|_{\omega = \omega_0} = \frac{\omega}{2}\left|\frac{d}{d\omega}\ln\frac{z_{11}(\omega)}{z_{12}(\omega)}\right|_{\omega = \omega_0} \to (2)$$

Where $z_{11}(\omega)$ and $z_{12}(\omega)$ are terms of the circuit impedance matrix Z.

As an example, a modified 50MHz Colpitts low phase noise crystal oscillator is discussed [17]. The equivalent circuit is shown in Figure 1.

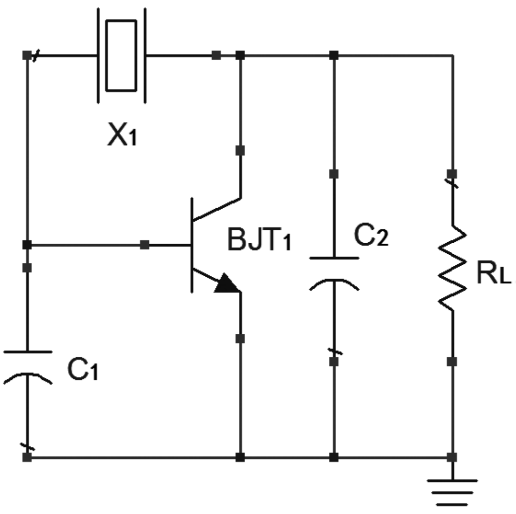

Figure 1. The equivalent circuit of Colpitts crystal oscillator.

In the above circuit, the crystal resonator X1 acts as an inductance L1. The equivalent circuit of passive network is shown in Figure 2.

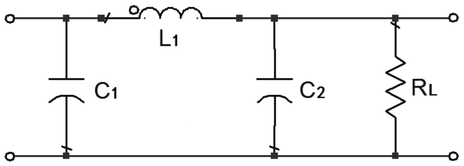

Figure 2. The equivalent circuit of passive network.

The impedance matrix Z of passive network in the circuit is expressed as follows:

$$Z = \frac{1}{(1-\omega^2L_1C_1)(1+j\omega C_2R_L)+j\omega C_1R_L}\begin{pmatrix} j\omega L_1(1+j\omega C_2R_L)+R_L & R_L \\ R_L & R_L-\omega^2L_1C_1R_L \end{pmatrix} \to (3)$$

According to (2) and (3), the result of Q_L is as follows:

$$Q_L = \frac{\omega}{2}\left|\frac{d}{d\omega}\ln\frac{z_{11}(\omega)}{z_{12}(\omega)}\right|_{\omega=\omega_0} = \frac{\omega_0}{2}\sqrt{\frac{L_1^2(4\omega_0^2C_2^2R_L^2+1)}{R_L^2+\omega_0^2L_1^2+\omega_0^4L_1^2C_2^2R_L^2-2\omega_0^2L_1C_2R_L}} \to (4)$$

From (4), we can draw a conclusion that Q_L would increase with C_2, that is to say, the larger C_2, the higher Q_L.

The simulation and design of colpitts crystal oscillator

The 50 MHz Colpitts crystal oscillator that its equivalent circuit is shown in Figure 2 is simulated by software ADS and the simulated phase noise curve is shown in Figure 3.

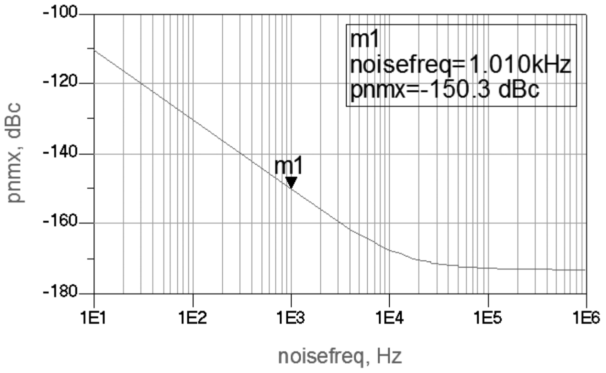

Figure 3. The simulated phase noise curve.

The value of C_2 is increased appropriately to improve the value of Q_L and reduce the phase noise. The simulated phase noise curve after adjusting C_2 is also presented in Figure 4.

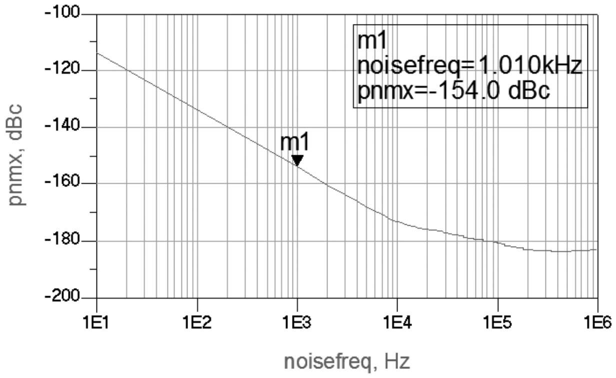

Figure 4. The simulated phase noise curve after adjusting C2.

Table 1. The parameters of crystal resonator.

Parameter	Value
Lq	0.012 H
rq	26 Ω
Cq	8.4×10^{-16} F
C0	2.2×10^{-12} F

According to the simulation results by ADS, the phase noise is decreased after adjusting C_2. Meanwhile, we can draw the conclusion that an appropriate increase in the value of C_2 will help to reduce the phase noise of this circuit. However, if C_2 is too large, the oscillation condition of the amplitude cannot be met and it is difficult to produce oscillation. Therefore in the allowable range, C_2 should be made as high as possible to reduce the phase noise. Based on the conclusions above, a prototype 50 MHz Colpitts crystal oscillator is designed. The AT-cut 3rd overtone crystal resonator with 49 U resistance welding package is used in the design and its quality is medium. Its parameters are as Table 1 and the value of unloaded quality factor Q_0 is about 1.45×10^5. The phase noise level of the 50MHz Colpitts crystal oscillator is measured by Agilent E5052B and it is shown in Figure 5.

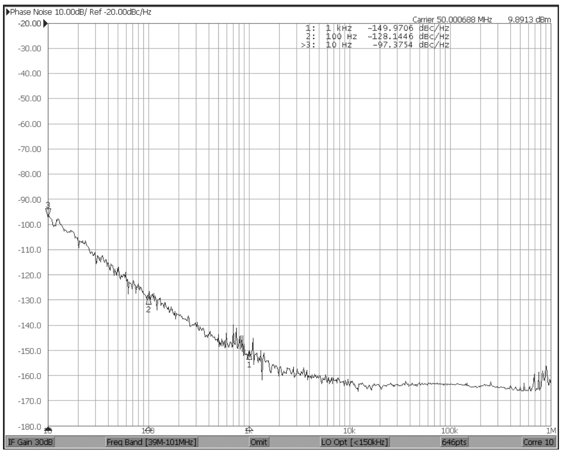

***Figure** 5. Measured phase noise curve of the 50MHz crystal oscillator.*

As in Figure 5, the measured results of phase noise are -97 dBc/Hz@10Hz, -128 dBc/Hz@100Hz and -149 dBc/Hz@1KHz. Based on above analysis, the value of capacitance C2 is adjusted to reduce the phase noise further. The measured results of phase noise level after adjusting C_2 are -107 dBc/Hz@10Hz, -134 dBc/Hz@100Hz and -152 dBc/Hz@1KHz and it is shown in Figure 6.

According to Figure 6, the phase noise is improving by adjusting the value of capacitance C_2. Though the crystal resonator used in the design is medium, the measured results of phase noise are relatively well and the crystal resonator's performance is realized as far as possible by the design based on improving Q_L.

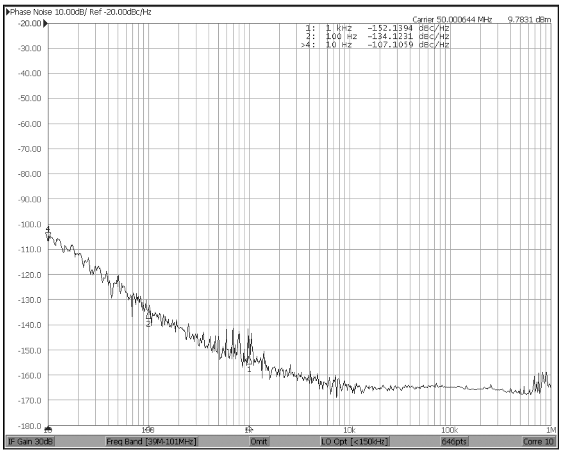

***Figure** 6. Measured phase noise curve after adjusting C_2.*

Conclusion

In this paper, the 50 MHz Colpitts crystal oscillator is designed on the basis of improving Q_L. Based on the simulation results by ADS, a design of the prototype 50 MHz crystal oscillator is presented and the experiments are carried out. By adjusting the value of capacitance C_2, the phase noise level is further improved and the performance of the crystal resonator is realized as far as possible. So it is feasible to design low phase noise crystal oscillators on the basis of improving Q_L.

Acknowledgment

This work is supported by application fundamental research fund of SiChuan Provincial Science and Technology Department (No. 2014JY0208) and scientific research starting project of SWPU (No. 2014QHZ026).

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