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Insertion Position Effect of Additional Quartz Resonator on Improvement of Phase Noise in Crystal Oscillator

水晶発振回路の振動子追加位置による位相雑音の改善

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1. Introduction

Quartz oscillators are widely used as stable frequency sources in communication systems. Advancements in mobile communication technology require quartz oscillators to perform low-phase noise characteristics. Much effort has been made to reduce oscillator phase-noise by contriving various circuit designs.

We have developed a method for reducing phase noise of Colpitts crystal oscillator and proposed a technique using the oscillation circuit with duplicated quartz crystal units for declining near-carrier phase noise. In our previous study, network analysis using the non-linear diode model and the phase noise analysis using the Leeson's model in Colpitts oscillation circuit with duplicated quartz crystal units were conducted[1]-[3]. As the results, it was clear that the phase noise could be improved when a capacitance (or an inductance) inserted to an oscillation circuit in series to an additional resonator was tuned. Possibility that the phase noise can be improved with a less volume of the total circuit by using two quartz resonators with small volume instead of one quartz resonator with large volume is presented. On the other hand, a possibility that the phase noise in the noise-floor region could be improved by using the Butler crystal oscillator and the Modified-Butler crystal oscillator as the VHF band oscillators.

Furthermore, we suggested that Butler oscillator with duplicated quartz crystal units has great phase noise whole of near carrier and floor and analyzed the phase noise of the suggested Butler oscillator. As a result, improvement of phase noise could be realized, then, insertion position effect of additional quartz resonator in Butler oscillator was considered to be the next subject.

We will reveal the difference of phase noise improvement between three insertion positions. In this paper, at first, an estimation method of the phase noise improvement is metioned in chapter 2. In chapter 3, Colpitts crystal oscillator with a duplicated crystal unit is denoted as a sample of our research. Then, in chapter4, details of three insertion positions are shown, and the results of the phase noise analyses obtained in cases of different two positions in the Butler oscillator are described.

2. Estimate Method of Phase Noise Improvement

To estimate improvement of phase noise, Butler oscillation circuit impedance was fit to oscillation condition, and differential value with frequency of circuit output impedance at oscillation frequency was applied to the Leeson's model.

To calculate the phase noise improvement, the circuit impedance must be adapted to the oscillation condition, i.e., formula (1).

$$\begin{cases}\mathrm{Re}(Z_{\mathrm{all}}) \leq 0 \\ \mathrm{Im}(Z_{\mathrm{all}}) = 0\end{cases} \tag{1}$$

Where, Z_{all} is the oscillation circuit impedance.

Next, the circuit output impedance, satisfying the oscillation condition, is applied to Z of formula (2), and the quality factor Q can be calculated.

$$Q = \left.\frac{\mathrm{d}\theta}{\mathrm{d}\omega}\right|_{\omega=\omega_0} \propto \left.\frac{\mathrm{dIm}(Z)}{\mathrm{d}\omega}\right|_{\omega=\omega_0} \tag{2}$$

Where, θ is the phase at oscillation circuit output, and ω_0 is the oscillation angular frequency.

Finally, the Q value is applied to the Leeson's model, formula (3), and the phase noise improvement is calculated as follows,

$$S_{\varphi}(f) = \frac{\alpha\left({}^{\nu_0}/_{2Q}\right)^2}{f^3} + \frac{\beta\left({}^{\nu_0}/_{2Q}\right)^2}{f^2} + \frac{\alpha}{f} + \beta \tag{3}$$

$$(\text{and, } \beta = 2FKT/Ps).$$

Where, S_{φ} is the phase PSD (Power Spectral Density), f is the offset frequency, ν_0 is the oscillation frequency, Q is the quality factor, α is the constant of $1/f$ noise level, β is the floor noise level, F is the noise figure, K is Boltzmann constant, T is the absolute temperature, and P_{S} is the power of the oscillator output.

3. Improvement of Phase Noise in Colpitts Crystal Oscillator with Duplicated Quartz Resonators

Fig. 1 is the Colpitts crystal oscillator circuit with the duplicated quartz crystal units. X2 is the additional quartz resonator. The phase noise could be tuned by C_{adj} which is located series to X2, and other elements.

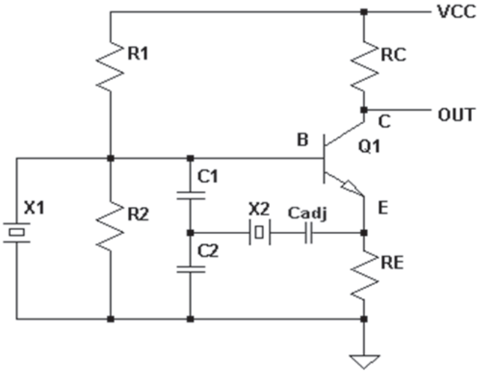

Fig. 1 Colpitts Oscillation Circuit with Additional Quartz Resonator

The additional quartz resonator produced the phase noise improvement of 12.4 dB (f_{offset} = 1 Hz) in the analysis. Common parameters of all quartz crystal resonator used in this analysis are shown in **Table 1**.

Table 1. Common parameters of all quartz crystal resonator used in this study

$R_q[\Omega]$	L_q[mH]	C_{q1}[fF]	C_{q0}[pF]	Q
8.836	0.368	6.875	2.028	26×10^3

4. Three Insertion Positions and Analysis Output in Butler Crystal Oscillator

A plain Butler oscillator circuit drawn in **Fig. 2** contains three insertion position of additional quartz resonator. In this analysis, the best circuit condition of the phase noise was explored by tuning the capacitance (C_{adj}, or inductance) and other circuit elements. C_B is replaced to the additional crystal unit X2, in the first insertion position, and, an inductor was added to be parallel to the X2 and C_{adj} to apply the bias voltage V_{CC} to the collector of a BJT (Bipolar Junction Transistor), in the second insertion position.

Qualitative explanations of the phase noise improvement for each of three insertion positions are given as follows. In the case of the first insertion position, selectivity of the base current is enhanced by the additional crystal resonator, and the phase noise can be reduced. On the other hand, in the case of the second and third insertion position, the additional quartz resonator is inserted in the oscillation loop, and the phase noise can be reduced. The cases of the second and third insertion position would have a better phase noise improvement than the case of the first one. However, the optimization of the phase noise is so difficult, because, two quartz crystal units are connected virtual series to each other.

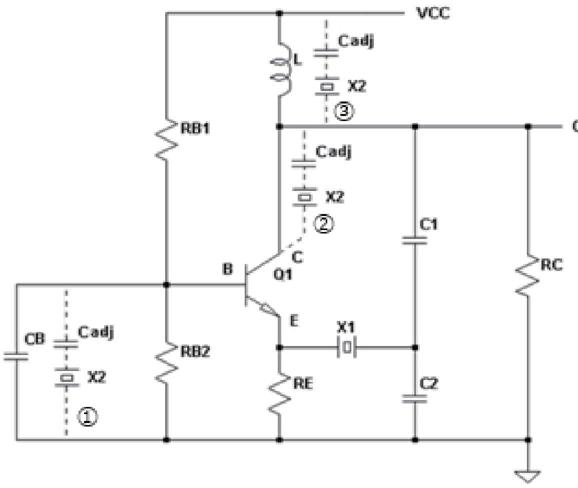

Fig. 2 Three Insertion Position of Additional Quartz Crystal Unit in a Plain Butler Oscillation Circuit

The improvements of the phase noise in the case of the first and second insertion positions were obtained as 7.1 dB and 13.6 dB respectively (f_{offset} = 1 Hz). The parameters shown in table1 were also used in this analysis.

5. Summary

In this research, three patterns of insertion position effect of the additional quartz resonator in the Butler oscillator were discussed. Two of three, namely the first and second positions were analyzed, and, obvious difference could be observed between the two patterns.

Fabrication of the Butler crystal oscillator with the additional quartz resonator at all of the three positions and measurement of improvement of the phase noise would be the future works.

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