Computer modeling of a biharmonic oscillator

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Abstract. In this work computer modeling of a two-mode Colpitts oscillator operating in the phase locking of two modes was carried out. Modeling of an oscillator operating modes and the experiment allow to draw a conclusion about possibility of phase noise reduction in a stationary synchronous biharmonic mode that can be used in the frequency stabilization task.

1. Introduction

Traditional methods of frequency stabilization use two main approaches: improving the stability of reactive parameters of the oscillator circuit and improving the Q-factor of the oscillating system. However, another way is possible, based on the phenomenon of mutual synchronization of waves in a two-mode oscillator. Earlier in [1] the method of phase noise reduction (PhN) of the oscillator, with synchronization of two modes in the biharmonic oscillator (BO) with multiple frequencies [2], has been described. It has been investigated under the assumption that the nonlinear element has no transit time effects.

The idea of the method of synchronization of the main oscillation with its 2nd harmonic with the auxiliary circuit is based [1] on the assumption that internal fluctuations in the active element (AE) modulate all current harmonics in one phase. Therefore it is possible to use this "natural" mutual correlation of noise processes in order to neutralize their influence.

It has been shown experimentally [3] that there is a decrease in PhN for BO on Gann diodes. Recent works [4, 5] have investigated the phase locking scheme of two nanoscale spintronic oscillators, for which the possibility of reducing the PhN in the phase synchronization mode has also been demonstrated. Therefore, the mechanism of phase and amplitude noise transformation during synchronization of oscillations is of great interest from the fundamental point of view for oscillators of different physical nature.

Figure 1a,b shows an example of a two-circuit oscillator and its poling curve. The poling curve shows the dependence of oscillation coupling frequencies ($\omega_i$) relative to the shock-excited frequencies of the resonant circuits ($\omega_{ih}$) in the two-mode oscillator. Assuming that the fluctuation in the output capacitance of AE will give rise to an increase in the frequency of the 1st oscillation, it will shift the operating point towards a decrease in the frequency of the 2nd oscillation. At the same time, the same capacitance change gives rise to the 2nd oscillation frequency, it will “pull” the 1st oscillation frequency towards the increase. Effects that occur in the system are directed in opposite directions, changing the frequencies of oscillations, and produce additional frequency stabilization.
In this article, to reduce the PhN, a BO circuit in a Micro-Cap environment was simulated to analyze the effect of the output capacitance of AE on BO modes and the locking range. As a result of modeling, a natural experiment on the transistor MMBT3904 was carried out, which showed the possibility of reducing the PhN by synchronizing the two modes in BO.

Analysis of characteristics of a typical microwave transistor has shown possibility of the simplified description of such AE in the form of a nonlinear element and the subsequent delay line where, in the first approximation, the delay of an output current is directly proportional to the harmonic number.

2. Oscillation system

The Oscillating System (OS) of BO consists of two connected resonance circuit. An example of such oscillating system is shown in figure 2. One resonant circuit is tuned to the main frequency (formed by C1, R1 and L1 elements), the other is tuned to almost a multiple of the 1st frequency (C2, R2, L2). Capacitance C2 takes into account the output capacity of AE.

The input reduced impedance to the characteristic resistance of the 2nd circuit of such a chain can be described by a formula:

\[
z = j \frac{\omega}{\omega_0^2} \left( \alpha_i \alpha_2 - \alpha_1 \left( \frac{\omega}{\omega_0} - \frac{\omega}{\omega_{01}} \frac{k_{21}}{k_{12}} \right) \right) \left( \frac{\omega}{\omega_0} + \frac{\omega^2}{\omega_{01} \omega_{02}} k_{21} \right)
\]

where \( k_{21} = L_2 / (L_1 + L_2) \) the 1st loop inclusion factor is in the 2nd loop, \( \alpha_i = \delta_i + j \cdot \nu_i(\omega) \), \( \nu_i(\omega) = \omega^j \omega_i + \omega_j / \omega \) - generalized disorder, \( \delta_i = 1 / Q_i \) - attenuation of circuits.

**Figure 1.** Equivalent scheme of BO and its poling curve.

**Figure 2.** BO schematic.
In figure 3 shows how the input reduced impedance of the OS BO changes with variation C1. We can see that there are 2 modes, the resonance frequencies of which depend on the capacity of C1. You can see that you can pick up a capacity at which the ratio of frequencies equal to 2 will be performed.

![Figure 3. The input reduced impedance of the oscillator system.](image)

3. BO simulation

A modeling of a BO circuit was performed in a Micro-Cap environment [11], where an n-p-n transistor MMBT3904 was used. The delay line (see Fig. 1a) is simulated by an RC-circuit in the transistor base circuit. Calculated voltage on the load, allows you to get the spectrum of output signal generated by the BO.

For two values $C_r = 0$ and 50 pF, the amplitudes and frequencies of the main generated signal ($A_1$ and $f_1$), its 2nd harmonic ($A_1^{II}$ and $f_1^{II}$), the generated signal at the additional frequency ($A_2$ and $f_2$) at a variation of the 1st resonant circuit capacitance were measured. Since the ratio of the fundamental frequency to its 2nd harmonic is always multiple of 2, the dependence of the 2nd harmonic frequency on the capacitance is not given in Fig. 4. In Fig. 5 presents the spectra of output signals at different values of C1 capacity. Points 1-3 in Fig. 5 correspond to the 1st harmonic of the main oscillation, and points 1'-3' to the 2nd harmonic of the main oscillation.

When the capacity of C1 changes from small to large values of about 180 pF at $C_r = 0$ pF (Fig. 4a) and C1 about 220 pF at $C_r = 50$ pF (Fig. 4b), you can see that the system is "captured" by the second circuit of the 2nd harmonic of the main oscillation, because there is a significant increase in the amplitude of the 2nd harmonic and the frequencies of the main oscillation and signal at the 2nd frequency are exactly a multiple.

At C1 capacity about 450 pF at $C_r = 0$ pF (Fig. 4a) and C1 about 380 pF at $C_r = 50$ pF (Fig. 4b) you can see how oscillation dumping. In the spectrum (see Fig. 5 3-3') of the output signal there are separate components of the 2nd harmonic - oscillation at the 2nd coupling frequency and many components at combinational frequencies. The amplitudes of the main frequency oscillations rapidly decrease as C1 increases further.
At values of capacity $C_1$ about 700/500 pF the oscillation of main frequency, and together with it its 2nd harmonic, disappear. That is, the self-excitation boundary of the main oscillation is not achieved, while the oscillation from the 2nd circuit exists. Thus, an increase of the delay, i.e. the $C_\tau$ capacity from 0 to 50 pF, resulted in a reduction of the BO system’s lock range from 870 to 500 kHz.

In figure 5 presents a series of spectra at different values of $C_1$ capacity. Points 1-1’ correspond to the signal at the main frequency and its 2nd harmonic. They are obtained at low capacity, where there is no synchronism mode and the boundary of self-excitation of the 2nd oscillation are not achieved. We can see that the amplitude of the 2nd harmonic is much lower than the amplitude of the 1st harmonic.

When you increase the capacity, you can see that the asynchronous mode turns to synchronous (2-2’), where there are 2 oscillations simultaneously existing. This is manifested in the fact that the amplitude of the 2nd harmonic, thanks to the 2nd circuit, became much larger and almost equal to the amplitude of the main frequency.

![Figure 4](image_url)  
\textbf{Figure 4.} Amplitudes and frequencies of signals at $C_\tau = 0$ pF (a) and $C_\tau = 50$ pF (b).

![Figure 5](image_url)  
\textbf{Figure 5.} Changing the spectrum when increasing $C_1$ at $C_\tau = 0$ pF.
4. Experimental results
Based on the results obtained in the Micro-Cap environment, an oscillator was constructed with the possibility of switching off the 2nd oscillating circuit to provide single-mode oscillator.

In figure 6 presents signal spectra at the output of oscillator in the two-mode (M1) and single-mode (M2) in the range of 5 - 25 MHz. The measurement was performed on the Rohde Schwarz FSV 7 GHz spectroanalyzer. The M1 signal corresponds to 8.8 MHz and M2 to 9.5 MHz. The main difference is the larger amplitude of the signal at the frequency of the 2nd harmonic of the main frequency, which is a sign of synchronization of oscillations of BO (see Fig. 5 1 → 2).

Figure 6. Spectrum at oscillator output in biharmonic and monoharmonic modes.

Figure 7 shows the noise spectral densities of single-mode (1) and two-mode (2) oscillator in the range from 10 Hz to 1 MHz. The measurement was performed on an Anapico PNA 26.5 GHz PhN meter. It can be seen that working in a two-mode oscillator reduces PhN by an average of 9 dBn/Hz. On the tuning ~0.5 kHz the PhN gain reaches up to 20 dBn/Hz.

Figure 7. Noise spectral densities in single-mode (1) and two-mode (2) oscillators.

Thus, the performed experimental research confirms the possibility of existence of a two-mode oscillator. This oscillation synchronization reduces the phase noise of the signals.

5. Conclusion
In this work, a modeling of the system of a two-mode oscillator was carried out. Two modes of operation were detected:
1. single-mode operation - when the signal at the output of BO has only the 2nd oscillation frequency corresponding to the 2nd harmonic of the main oscillation;
2. two-mode operation - 2 oscillations coexist with exactly multiple frequencies and non-zero amplitudes.

It has been experimentally shown that the biharmonic mode allows reducing the phase noise of the main oscillation to 20 dBn/Hz, which corresponds to the theoretical assessment.

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References
[1] Tsarapkin D P, Chichvarin M I and Isakov I A 2000 Experimental verification of compensation phenomena in oscillators with two multiple modes Proc. 2000 IEEE/EIA IFCS, 7-9 June 2000 (USA: Kansas City, MO) 463–470
[2] Utkin G M 1978 Self-oscillating systems and wave amplifiers (Moscow: Sov. Radio)
[3] Karachev A A, Levchenkov O I and Tsarapkin D P 1977 An experimental study of the two-frequency mode of the Gunn generator Transactions of MPEI Radio transmitting and receiving devices (Moscow.: MPEI) 317 36–38
[4] Mitrofanov A A, Safin A R, Udalov N N and Kapranov M V 2017 Theory of spin torque nano-oscillator-based phase-locked loop Journal of applied physics 122 123903
[5] Mitrofanov A A, Safin A R and Udalov N N 2015 Amplitude and phase noises of a spin-transfer nano-oscillator synchronized by a phase-lock loop Tech. Phys. Lett. 41 778