Influence of Resonator Factors on Phase-Noise of OCXOs

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The paper is devoted to study of physical causes of phase-noise of crystal oscillators associated with the crystal technology. It was found that this source contributes into the phase-noise though instability of the quartz - electrodes transition (QET) modulating the crystal parameters. A model linking the oscillator frequency fluctuations with instability of QET, equivalent parameters of the crystal, and some regimes of the sustaining circuitry was proposed and confirmed experimentally. Basing on this approach some ways of phase-noise reduction were proposed and discussed in the paper.

I. INTRODUCTION

Reduction of phase-noise of OCXOs has become nowadays one of the most important problem and subject of permanent efforts of researchers in the field. For a long time main noise sources of the phase-noise were associated with the sustaining circuitry while the crystal was considered as a noiseless filter element included in the oscillator feedback [1]. Although based on such approach Leeson's model proved its correctness for many practical cases a lot of experimental data don't obey predicted 30 dBc/decade slope in the crystal bandwidth exhibiting in reality up to 40 dBc/decade rate. Such discrepancy stimulated a search for alternative noise sources associated with physical properties of the crystal.

As possible mechanism causing degradation of phase-noise of an OCXO influence of temperature fluctuations of the oven construction on the crystal frequency via the thermodynamic effects was studied in many works. There was concluded that effect of thermodynamic factors on the phase-noise becomes substantial only at rather slow - below 0.1 Hz – fluctuations of the oven temperature and can be neglected at above 1 Hz frequency [2].

Another approach considering fluctuations of the crystal's equivalent parameters as main noise source was described in [3]. Proposed by the authors model provided adequate description of an oscillator phase-noise pattern basing on noise factor of motional resistance and capacity of the crystal. However physical causes of the fluctuations of the crystal parameters were not taken into account that didn't allow elaboration of any methods of phase-noise reduction.

Meantime many researchers noticed distinct correlation of the oscillator phase-noise properties with state of the transition between crystal surface and the film electrodes depending on quality of the surface and the film deposition process [4]. The idea of quartz-electrode transition (QET) as substantial factor of the oscillator phase-noise was confirmed by testing "electrodes-less" designs exhibiting utmost figures of the phase-noise and short-term stability [5].

A goal of the present work was experimental study and modeling of OCXO phase-noise factor associated with QET instability and basing on this ground elaboration of practical methods of phase-noise reduction.

II. EXPERIMENTAL STUDY OF RESONATORS PHASE-NOISE

To prove the crystal is a substantial source of an oscillator phase-noise providing additional rate to predicted 30 dBc/decade slope of the phase-noise pattern, we tested a number of 10 MHz SC-cut OCXOs comparing slope of their phase-noise patterns with the phase-noise level at 1 Hz offset. The results are depicted in fig.1.

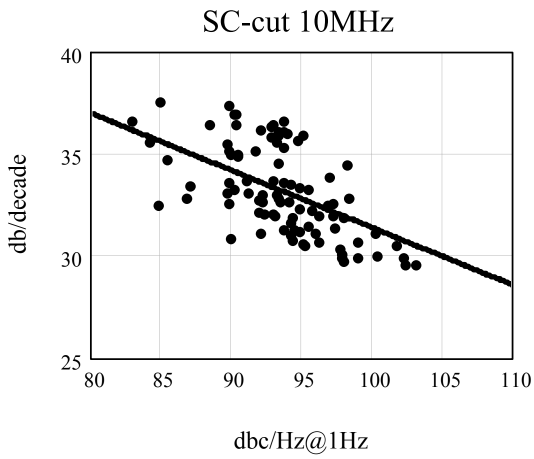


Fig. 1. The slope of OCXOs phase-noise patterns versus the phase-noise level measured at 1 Hz offset

As it follows from the data the rate of the slope falls with decrease of the phase-noise level approaching the "theoretical" 30 dBc/decade at about –105 dBc. Obviously higher than –105 dBc level of the OCXO noise should be related to the crystals intrinsic noise factors.

Indirect evidence of predominating role in the noise of factors associated with the crystals surface was derived by study of two batches of OCXOs using AT-cut 3d overtone crystals operating at 5 MHz and packaged in TO-8 holders. The OCXOs were divided into two groups differing in mounting structure of the crystals. While one group consisted of the crystals with two-point fixture of the blank another group contained crystals with four-point fixture. The difference in the blanks fixtures resulted in difference of the crystals Q-factor value measured about 1.5 million for two-point fixture and about 1.2 million for four-point fixture. Phase noise test results of the OCXOs are depicted in fig.2.

As it follows from the statistical data best figures for both groups reach about - 108 dBc at 1 Hz offset that roughly corresponds to best results achieved in similar oscillator design with 10 MHz 3d overtone SC-cut crystals in spite of essentially worse thermodynamic properties and drive level dependence (DLD) of the AT-cut resonators.

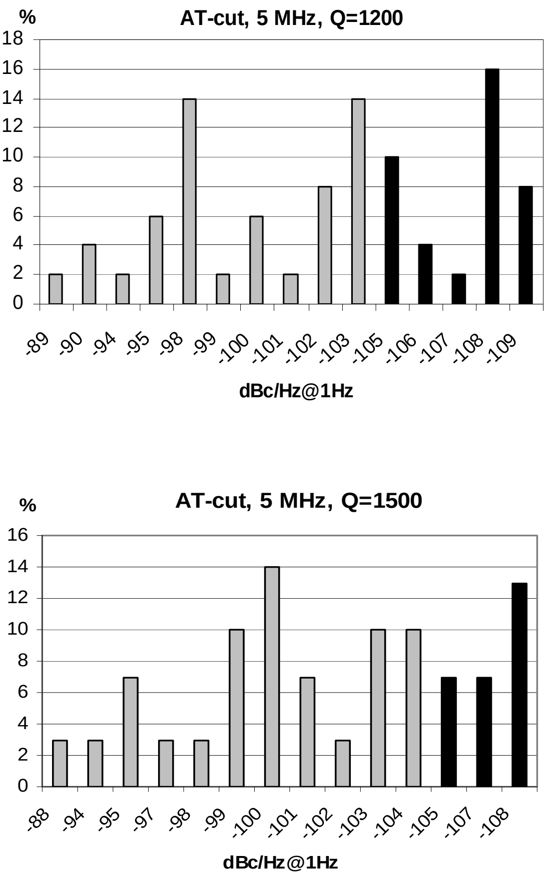
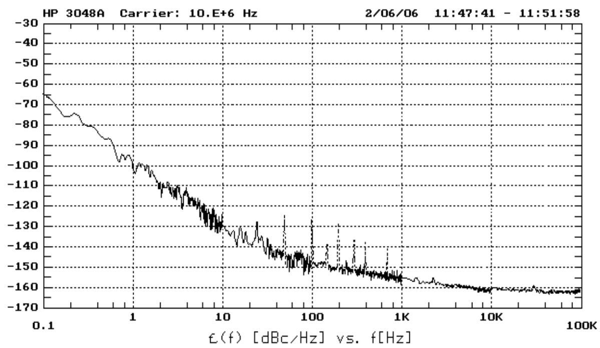


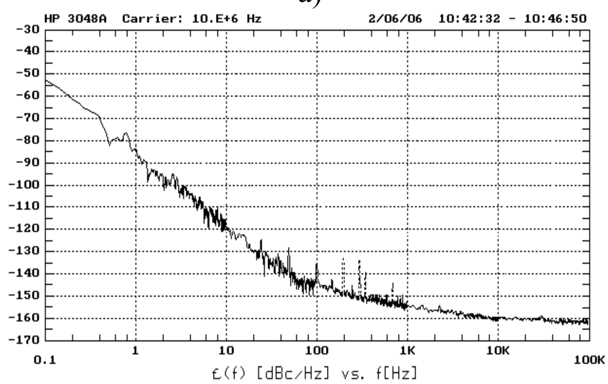
Fig. 2. Phase-noise test data of 5 MHz 3d OT AT-cut crystals

Another deduction drawn from the experimental data is some advantage of OCXOs using "low" Q-factor crystals over ones with "high" Q-factor units. While the first batch includes about 40% of units with better than –105 dBc phase-noise, the seconds have only 27% of the "low-noise" units. Such results can not be understood by Lesson's theory, but will be explained latter by the crystals intrinsic noise.

As was stated in many works the most substantial noise source associated with the crystal technology originates from instability of the quartz-electrodes transition (QET). Assuming that roughness of the crystal surface should be influential factor of QET instability we studied phase-noise of two groups of 10 MHz SC-cut crystals with different finish of their surfaces. While one group contained the units with perfectly polished surfaces another group consisted of crystals with 1μ finish surfaces. All the units passed through same fabrication process including microscope inspection of electrode deposition quality. Phase-noise of crystals was measured in special low-noise test design containing the oven to sustaining the crystals temperature within 0.2˚C about the turn-over point. Typical phase-noise patterns obtained with best units of each group are depicted in fig. 3.



a)



b)

Fig. 3. Comparative phase-noise tests of SC-cut crystals with different surface quality: a) typical phase-noise pattern for best units with polished surfaces;
b) typical phase-noise pattern for best units with 1μ finish surfaces.

As it follows from the data phase-noise figures for the best units with polished and 1 um finished surfaces differ for about 15 dBc at 1 Hz and 10 dBc at 10 Hz offset. Moreover the polished crystals provide within 0.1-10 Hz offset about 30 dBc/decade slope while the 1µ finished ones exhibited about 35 dBc/decade that implies existence of additional noise source inherent with the crystal surface.

III. MODELING THE INFLUENCE OF QUARTZ-ELECTRODES TRANSITION ON AN OSCILLATOR PHASE-NOISE

Carried out experimental study revealed predominating role of QET on the resonator noise properties. Obviously defects of the crystal surface, contaminations, and micro-particles under the electrode film and failures of the deposition process should lead to deterioration of adhesion properties of the electrode film. That results into additional dissipation of the oscillation energy and incomplete compensation of the surface charges impacting on the crystal's motional resistance and capacitance. Obviously under variation of temperature, mechanical stresses or vibrations of the crystal surface the state of QET may change that, in turn, should lead to fluctuations of the crystal parameters and the oscillator frequency.

Described physical model can be represented by equivalent network of the crystal depicted in fig. 4, where δR_q determines fluctuating part of losses in QET, C_{qe} is capacitance of QET, δC_{qe} is fluctuating part of C_{qe}.

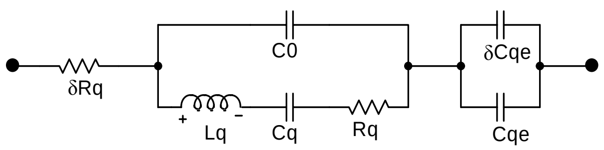


Fig. 4. Equivalent network of a crystal with QET fluctuations.

To define fluctuation of the crystal equivalent parameters caused by instability of QET state Q-factor of the crystal can be expressed as ratio of its kinetic energy W and sum of energies dissipating in quartz structure (E_q), in the quartz-electrodes transition (E_{qe}) and in the crystals periphery (E_p):

$$Q = W / (E_q + E_{qe} + E_p), \qquad (1)$$

Differentiating (1) by E_{qe} and performing simple transformation a variation of Q-factor versus variation of E_{qe} can be expressed as:

$$\frac{\delta Q}{Q} = -\delta E_{qe} \cdot \frac{Q}{W}, \qquad (2)$$

The energy lost in the film electrodes can be written as portion η of kinetic energy stored in the vibrating film (We):

$$\frac{\delta Q}{Q} = \delta(\eta \cdot W_e) \cdot \frac{Q}{W} = \delta\eta \cdot Q \cdot \frac{M_e}{M_q} = \frac{\gamma}{\Omega^k} \cdot Q \cdot \frac{M_e}{M_q}, \qquad (3)$$

where $\delta\eta = \gamma/\Omega^k$ – fluctuation of energy lost in the film electrodes depending on value and density of defects in QET and obeying the flicker law; M_e and M_q – masses of the film electrodes and the quartz plate in the active area of the crystal.

As $\delta Q/Q = \delta R_q/R_q$ expression for (3) is also valid for simulation of the motional resistance variations.

For estimation of fluctuations of QET capacity we assumed that relative value of the fluctuation $\delta C_{qe}/C_{qe}$ should be in direct proportion with relative fluctuations of energy dissipating in the electrodes and then can be expressed as:

$$\frac{\delta C_{qe}}{C_{qe}} = \frac{\gamma}{\Omega^k} \cdot \psi, \qquad (4)$$

where Ψ is some function linking relative variation of dissipating in the film energy with fluctuation of QET capacitance.

Substituting (4) into well-known expression for deviation of a crystal frequency caused by series connected capacitance (C_{qe} in our case) and taking into account that value of C_{qe} much exceeds the crystal shunt capacitance we comes to expression for crystal frequency fluctuation versus QET capacitance variations:

$$\frac{\delta F}{F} = \frac{\delta C_{qe}}{C_{qe}} \cdot \frac{C_q}{2C_{qe}} = \frac{\gamma}{\Omega^k} \cdot \psi \cdot \frac{C_q}{2C_{qe}}, \qquad (5)$$

While variation of QET capacitance C_{qe} impacts on the oscillator frequency directly, variations of motional resistance and Q-factor produce frequency fluctuations via FM and AM of the drive current. The latter induces the frequency fluctuations through non-linearity of the varactor (in case of its usage) and DLD of the crystal.

Expressing the oscillator frequency fluctuations caused by modulation of the oscillation phase, varactor capacitance and DLD of the crystal via functions Φ_φ, Φ_v and Φ_{DLD} complete expression for the frequency fluctuations caused by QET instability can be written as:

$$\frac{\delta F}{F} = \Phi_\varphi\left(\frac{\delta Q}{Q}\right) + \Phi_v\left(\frac{\delta Q}{Q}\right) + \Phi_{DLD}\left(\frac{\delta Q}{Q}\right) +$$

$$+ \frac{\gamma}{\Omega^k} \cdot \psi \cdot \frac{C_q}{2C_{qe}}, \qquad (6)$$

Equations (3) and (6) in fact represent considered above physical model in terms of functional relationships. Although accurate definition of functions Φ_φ, Φ_v, Φ_{DLD} and Ψ is a difficult task and a subject of future researches the model links fluctuations of the oscillator frequency with equivalent parameters of the crystal as well as with some regimes of the sustaining circuitry. Analysis of the model performed below allows better understanding observed phase-noise behavior of oscillators as well as leads to some methods of phase-noise reduction.

IV. ANALYSIS OF THE MODEL AND METHODS OF PHASE-NOISE REDUCTION

As it follows from considered model instability of QET defined by factor γ is main efficient of all expression for the crystal parameters variations. Then all improvements of polishing, cleaning, and film deposition processes providing reduction of this noise factor should result in decrease of the crystal noise.

Uncommon conclusion coming from the model is direct dependence of fluctuations of the crystal parameters on Q-factor at constant value of noise factor γ. This theoretical deduction was confirmed by experiments including one described above where better phase noise of OCXOs was reached with "lower" Q-factor AT-cut crystals. The phenomena can be understood from the fact that improvement of Q-factor of two-point fixture units was reached without reduction of energy losses in QET that even increased fluctuating portion of dissipated energy in the crystals.

Important conclusion drawn from the model is dependence of QET contribution into the crystal noise on the electrodes mass/crystal mass ratio. Hence minimization of the electrode mass and use of high overtone crystals should bring advantageous in phase-noise properties. Another argument in favor of the high-overtone crystals following from the model is essentially lower value of their capacitance resulting in reduction of the frequency fluctuations due to QET variations. To prove this conclusion we tested a group of 10 MHz 5th overtone SC-cut crystals fabricated with careful control of the polishing and deposition process. Typical phase-noise pattern for best measured units are depicted in fig. 5.

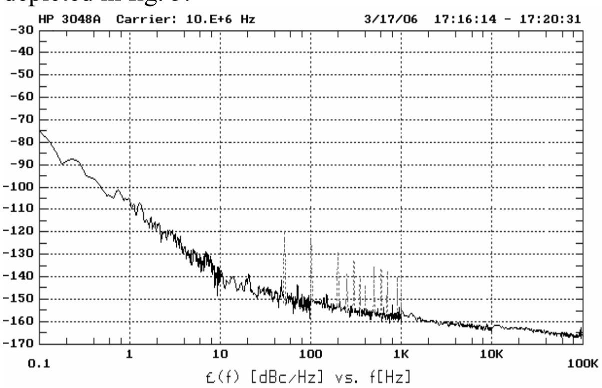


Fig. 5. Best phase-noise figures obtained with 5th overtone 10 MHz SC-cut crystals

As it follows from obtained results the 5th overtone crystals exhibit about –110 dBc at 1Hz and - 140 dBc at 10 Hz offset. These figures are about 6 dBc better than those obtained with best 3d overtone SC-cut crystals (fig. 3) that proves advantageous of the high-overtone crystals for low-noise applications.

CONCLUSION

1. Influence of quarts-electrode transition of the crystals was experimentally proved to be predominating factor of the oscillator near-the carrier phase-noise causing essentials (to 20 dBc) spread of the phase-noise figures due to imperfections of the crystal technology.

2. The model linking the oscillator frequency fluctuations with QET instability, the crystal parameters as well as with some sustaining circuitry regimes has been proposed and discussed in the paper.

3. Some ways of the phase-noise reduction following from the proposed model such as usage of high overtone crystals, low-mass electrodes, and others been suggested and confirmed experimentally.

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