STUDY OF PHYSICAL CAUSES OF INTERMODULATION DISTORTIONS IN HFF CRYSTAL RESONATORS

I. Abramzon, S. Pilshchicov, O.Rotova, S.Rudenko

"Magic Crystal Ltd", 18 K. Marx av., bld. 29, Omsk 644046, Russia
E-mail: mxl@omsknet.ru

Keywords: Quartz filter, HFF crystal, intermodulation, non-linearity

Abstract

The paper is devoted to experimental study of non-linearity of HFF crystal units and its influence on the quartz filter intermodulations. On statistical treatment of the measurement data the regression coefficients linking the crystal parameters non-linearity with the intermodulation level have been defined. The origin of the crystal non-linearity was explored through standard fabrication process stages. It was deduced that a main source of the non-linearity most probably arises during the electrodes deposition as the film imperfections creating some flicking capacitance and resistance depending of crystal vibration amplitude. Some ways of reduction of the crystal non-linearity are proposed and discussed in the paper.

1 Introduction

The intermodulation distortions in quartz filters being a substantial factor of degradation of sensitivity and selectivity of FM receivers remain in a focus of scientist and engineer efforts for many last years. As a main source of the phenomena non-linearity properties of the quartz resonators is a major subject of the investigations. In a number of works devoted to the crystals non-linearity the frequency and motional resistance drive level dependence (DLD) are considered as only evidence of the non-linearity, however without strong correlation with the intermodulations level [1, 2].

Physical causes of the frequency DLD and anomalies in motional resistance vs. dissipated power behavior were thoroughly explored in numerous works. Starting from quartz material non-linearity and the structure imperfections as main causes of the phenomena in the first works some authors came later to idea of influence on the main vibration mode of some surface masses capable of movement under the crystal vibrations [3]. Based on this idea physical model allowed satisfactory explanation of some non-linear phenomena in the crystal resonators was developed. At the same time apparent couple of the non-linearity effects with fabrication process of the resonator has not been revealed.

The goal of the present work was an attempt to develop a model linking the filter intermodulations with non-linearity of the crystal resonator parameters basing on statistical analysis of the experimental data. Upon this method of the non-linearity evaluation we attempted to deduce main fabrication process factors producing the non-linear effects as well as to develop a physical model explaining observed phenomena. On the base of obtained knowledge of the phenomena some ways of "improvement" of linearity of HFF crystals were proposed and evaluated.

2 Phenomenon model of intermodulations in the quartz filter

Since the intermodulation distortions of a quartz filter result from passing of two different frequency signals through the crystal unit the non-linearity of its parameters should define level of the intermodulation spectral products. Schematic drawing of simplest quartz filter is depicted in Fig.1. In general case the equivalent circuit of the crystal resonator consists of non-linear motional resistance R1, motional capacitance C1, motional inductance L1 and shunt capacitance C_0 which values depend on amplitude of passing through the filter signals. The crystal's resonance frequency f_0 fully defined by above parameters has however own dependence on the signal amplitude known as DLD.

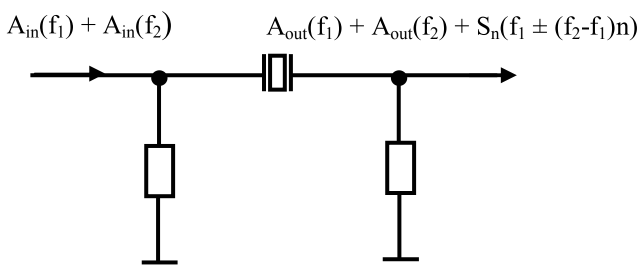


Fig.1. Schematic drawing of the simplest quartz filter.

In dependence on order of the crystal non-linearity the output spectra of two harmonic signals passing through the filter contains different set of spurious modes. In case of the third-order non-linearity a two-harmonic signal $A^{in}(f_1)$, $A^{in}(f_2)$ produces besides the same signals $A^{out}(f_1)$, $A^{out}(f_2)$ with their odd harmonics a set of intermodulation products with frequency $f_1 \pm (f_2 - f_1)n$ $(n = 1,2\ldots\infty)$ and amplitude S_n, depending on the input signals and the non-linearity value of the crystal parameters.

Relationships between the crystal non-linearity and the intermodulation products level can be defined on solving the differential equations for passing the signals through the non-linear resonance circuit. Another approach can be based on statistical analysis of experimental data obtained with measurements of intermodulation spectra of a number of crystal units with different values of their non-linearity.

The third-order nonlinearity of the crystal parameters means its quadratic dependence on the driving current and can be determined via the non-linearity coefficients calculated as:
$Nf = R1(\Delta f/f)/P$, $Nr = \Delta R1/P$, $Nc = R1(\Delta C1/C)/P$,
$N_L = R1(\Delta L1/L)P$, $Ns = R1(\Delta Cs/Cs)P$, where Δf, $\Delta R1$, $\Delta C1$, $\Delta L1$, ΔCs are deviation of the parameters caused by change of the driving power from 0 to P; R1, C1, L1, f1, Cs – equivalent parameters measured at low power.

One should note that correct estimation of the non-linearity coefficients requires monotonic and smooth shape of the parameter versus drive level behavior as well as correspondence of the measurement power P to amplitude of signals passing though the quartz filter. Obviously for in-band and out-of band signals brining essentially different values of the current through the crystal unit appropriate values of the measurement power should be used resulting in different non-linearity coefficients.

Using the defined coefficients relative level of the intermodulation product S_n/A^{out} can be linked with the crystal non-linearity through a set of regression equations:

$$\left(\mathbf{S_n}/\mathbf{A^{out}}\right)_{\mathbf{i}} = \mathbf{K_r N_{ri}} + \mathbf{K_C N_{Ci}} + \mathbf{N_{Li}} + \mathbf{K_f N_{fi}} + \mathbf{K_S N_{Si}}, \quad (1)$$

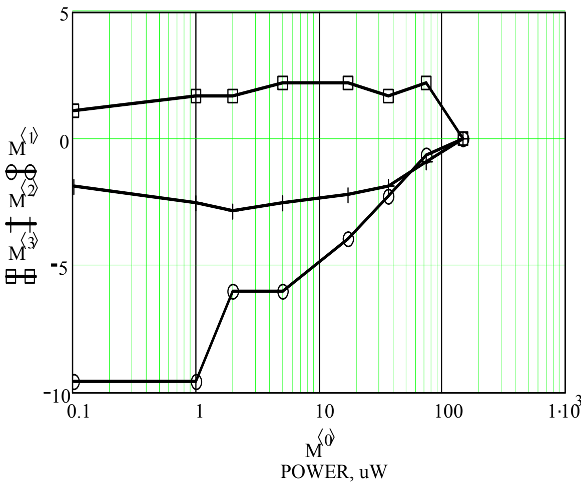
where $(S_n/A^{out})_i$- intermodulation *n*-product level measured with *i*–crystal unit having non-linearity coefficients N_{fi}, N_{ri}, N_{Ci}, N_{Li}, N_{Si}; K_r, K_C, K_L, K_f, K_S – coefficients of influence of the parameter non-linearity on the intermodulation product level.

Applying the correlation and regression analysis to the experimental data obtained with sufficient number of the units one can determine the influence of all the non-linearities on the filter intermodulation level.

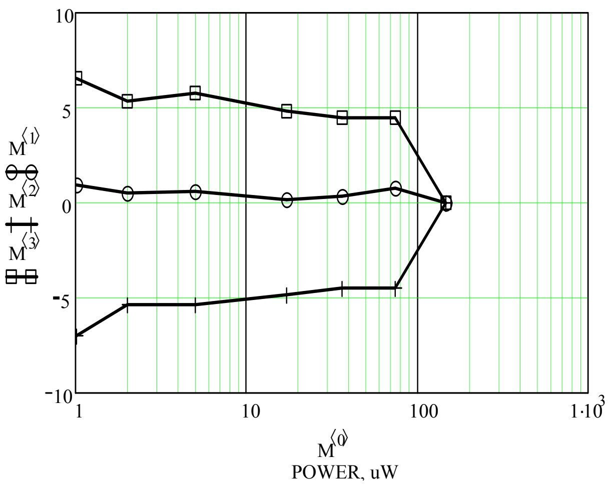
As it follows from above expressions the influence coefficients do not depend on the crystal non-linearity but are stuck with the filter configuration and the circuit parameters.

On the base of considered method we studied influence on the filter intermodulation of the HFF crystals operating at 65-160 MHz frequencies and fabricated with the standard process. The carried out researches didn't reveal any nonlinearity of the shunt capacitance. The DLD of the crystal resonance frequency appeared to be conventional for the kind of units and didn't indicated distinct correlation with the intermodulation level for the most cases but seldom ones where sharp anomalies of the DLD were observed.

At the same time the motional parameters of the crystals revealed noticeable changes under the driving power essentially varying between the units and correlating with the filter intermodulation level. Typical dependences of the crystal parameters are depicted in fig.2.



a)



b)

Fig. 2. Typical DLD of equivalent parameters of HFF resonators N_r (corresponds to $M^{\langle 1\rangle}$), N_L (corresponds to $M^{\langle 2\rangle}$), N_C (corresponds to $M^{\langle 3\rangle}$): a) unit #1 with "high power" non-linearity; b) unit #2 with "low power" non-linearity

As one can see from the curves unit #1 indicates greater non-linearity at low power level producing out-of band filter intermodulation, while unit #2 is more sensitive to high power variation that should be a cause of in-band intermodulation. Another corollary following from the researches is that the capacitance and inductance non-linearity are of almost equaled values and opposite sign, i.e. $N_C = - N_L$. This fact along with above conclusions allows study of the crystal non-linearity basing only on two coefficients N_r and N_C (or N_r and N_L).

3 Experimental study of the non-linearity origins through the fabrication process

As it follows from previous analysis the non-linearity of the crystals vary significantly between the units that is obvious result of influence on the parameters of the fabrication factors. To evaluate influence of the factors we've traced the non-linearity through the standard fabrication process.

As possible contributors into the crystal's non-linearity the main process stages such as chemical etching the inverted mesa-structure, base-plating the electrodes and final frequency adjustment were investigated.

To define possible impact of the etched surfaces into the non-linearity we measured the non-linearity coefficients N_r, N_C for two groups of HFF crystals after base-plating procedure. The first group consisted of the units coated with Cr-Ag electrodes just after the chemical etching. Second one contained only "linear" units selected from the first group and recoated with new electrodes after chemical removing first ones. Statistical treatment of measured non-linearity coefficients for the average value and the variance doesn't reveal essential difference of the group that is evidence of negligible contribution to the non-linearity of the etched surface conditions and priority of the base-plating factor.

Basing on the observed results a set of experiments with different electrodes geometry, material kind and the deposition methods were realized to link value of the influence with parameters of base-plating process. Table 1 represents average values N_r, N_C measured at ranged from 10 to 150 uW power in dependence on the electrodes features.

As one can see from the data best linearity is achieved with the Al and Ni-electrodes at some degradation of the parameter with raise of the film thickness. Taking into account essentially worse adhesion properties of Ag film we can presume that its greater influence on linearity is may be by detach from the crystal surface of some film parts mismatching the adhesion layer. The detached film parts forced to movement by the crystal plate vibrations

Material of the electrodes	*Mass loading %*	*Deposition method*	*Average values of non-linearity coefficients*	
			N_r, Ohm/W	*N_C, Ohm /W*
Cr- Ag	1.5	Thermal evaporation	$4.47*10^{-3}$	$3.24*10^{-3}$
Cr- Ag	3.0	Same	$6.84*10^{-3}$	$4.73*10^{-3}$
Cr- Ni	3.0	Magnetron	$4.72*10^{-3}$	$1.92*10^{-3}$
Al	0.7	Thermal evaporation	$2.49*10^{-3}$	$1.44*10^{-3}$
Al	1.5	Same	$4.7*10^{-3}$	$2.17*10^{-3}$

Table 1: Average values N_r, N_C in dependence on electrodes features.

create flicking capacitance of the crystal-electrode junction modulating the motional reactance of the crystal unit. The presumption was confirmed by experiment with deposition on the crystal units of Ag-electrodes without adhesive layer. Measurement of the unit linearity indicated cardinal degradation of the parameter.

Dependence of the non-linearity on the electrode sizes displayed inverse proportion at the high driving power that can be obviously explained by decrease of the driving current density followed by lower vibration amplitude. At the same time we didn't noticed any dependence on the electrode sizes at low levels of the driving power.

To explore influence on the crystal non-linearity of the final adjustment procedure we tested a few groups of the units base-plated with Al and Cr-Ag electrodes and final plated with Al, Au or Ag materials. On analysis of the experimental data we've come to a conclusion of small impact of the procedure on the non-linearity for all the materials that probably can be explained by rather small mass loading value of about 0.1% of the crystal frequency.

4 Physical model of HFF crystal non-linearity and the process improvement

On the base of the experimental results one can deduce some features regarding nature of the HFF crystal non-linearity as well as its origin in the fabrication process. Obtained data on the crystal motional reactance behavior (changes under the driving power, independence on ambient temperature and dependence on the electrode adhesion properties) allowed presumption of the non-linearity model based on influence of poor adhesive parts of the electrode film on the crystal parameters. Forced to vibration by the crystal resonance mode the electrodes free parts create the flicking capacitance in the crystal-film junction modulating the motional reactance of the crystal. Besides the vibration of the electrode parts causes fluctuation of the plate mode energy dissipation in the film resulting in flicking resistance included into the crystal circuit. Electrical model of the non-linearity is depicted in fig. 4.

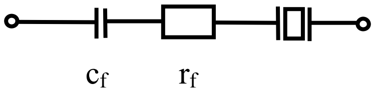


Fig. 4. Electrical model of the crystal unit non-linearity: Cf –the flicking capacitance of the crystal-electrode junction; Rf – the flicking resistance.

Average value of the flicking capacitance decreases with raise of the vibration amplitude that results in increase of the motional inductance, resistance and resonance frequency. The raise of the parameters vs. driving power was observed during described above experiments (fig. 2).

The electrodes deposition procedure is proved to be a main source for the poor adhesive film parts that explains the fact that the non-linearity depends on the film material and the deposition method. The Cr-Ag structure appeared to be worse option for the high-linear unit process comparing with aluminum or nickel materials.

Obviously removing the free fractions off the electrodes surface should improve the crystal linearity. That can be done by "cleaning" the electrode surfaces with ion-plazma etching procedure. Results of application of this method are depicted in fig. 5. As one can see noticeable improvement of the linearity appears at evaporation depth of about 30% of the electrode mass.

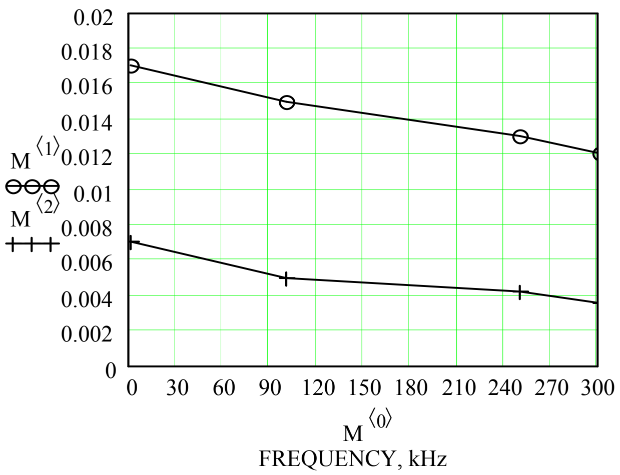


Fig. 5. Dependence of non-linearity coefficients N_r (corresponds to $M^{\langle 1\rangle}$), N_C (corresponds to $M^{\langle 2\rangle}$) on the electrode mass removing at initial mass-loading of 1 MHz.

Conclusion

1 The intermodulation distortions of quartz filters can be estimated on measurement of DLD of equivalent parameters of the crystal units R1, C1 and Ll. Meantime the unit's frequency DLD indicates only essential anomalies of the linearity.

2 Physical model of the non-linearity based on idea of flicking capacitance of the crystal surface-electrode junction created by poor adhesive electrode parts and flicking under the crystal vibrations was proposed and confirmed during the research.

3 An effective way of reduction of the non-linearity is a choice of high adhesive materials for the electrodes deposition and the final plating as well as plasma cleaning the electrodes surface from the poor adhesive fractions.

References

[1] E.Hafner, "Some phenomena in VHF crystal units", *Proc. 10th AFCS*, pp. 182-189, (1956).

[2] L.Dworsky, G.Kinsman, "A Simple Model for Quartz Crystal Resonator Low Level Drive Sensetivity and Monolotic Filter Intermodulation", *Transactions on UFFC*, **vol. 41**, pp.261-269, (1994).

[3] W.C. Horton, R.C.Smyth, "Experimental investigation of intermodulation in the quartz filters", *Proc. 27s AFCS*, pp. 180-186, (1972).