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STUDY OF NOISE CHARACTERISTICS OF BAW AND SAW QUARTZ RESONATORS*

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The low-frequency noise of bulk- and surface-acoustic-wave (BAW and SAW) resonators at frequencies of from 100 to 600 MHz is studied. It is shown that both SAW and BAW resonators have parameter (resonant-frequency) fluctuations with 1/f power spectra with considerable intensity spreads: approximately 20 dB for SAW and more than 30 dB for BAW resonators. The phase-noise floor of 100-MHz oscillators with BAW resonators is −150 dB/Hz for a 1-kHz offset frequency. The phase-noise level of oscillators with SAW resonators at 400-600 MHz is higher by 5-10 dB (scaled to a 100-MHz carrier frequency).

Noise in crystal-controlled oscillators with surface- and bulk-acoustic-wave (SAW and BAW) resonators is a serious problem for developers of electronic equipment. A considerable number of foreign publications ([1-3], for example) have been devoted to this problem. Information on noise in oscillators with BAW and especially SAW resonators is very scarce in the domestic literature.

We shall describe an experimental study of noise in oscillators with SAW and BAW resonators to determine the role of resonator noise and estimate its contribution, to compare the noise of SAW and BAW resonators, and seek the causes of resonator noise.

The procedure for estimation of resonator noise was based on measurements of the phase noise of oscillators with SAW and BAW resonators and the noise of frequency discriminators based on these resonators. Two apparatuses were constructed for these studies. The first apparatus – for measurement of the noise of SAW oscillators – was based on heterodyne detection with an intermediate frequency of 0.1-0.5 MHz. The frequency detector was implemented by an LC circuit (tunable in the frequency band of 0.1-0.5 MHz) and a low-noise phase detector. The local oscillator was either a crystal-controlled with frequency multiplication or an SAW oscillator similar to that studied with a frequency difference of 0.1-0.5 MHz.

The second apparatus – for measurement of the noise of SAW and BAW oscillators – was based on direct frequency detection. The frequency detector employed an SAW or BAW resonator and a low-noise wideband phase detector (operating at 0.1-1 GHz). Two resonators with identical frequencies were used in the measurements – one for the oscillator and the other for the frequency detector. An S5-3 or SK4-56 low-frequency spectrum analyzer was connected to the outputs of both apparatuses. The measured spectra were converted to the phase-noise spectra of the studied oscillators or the parameter-fluctuation spectra of the resonators.

The low-noise phase detectors have been described elsewhere [4]. The SAW oscillators employed two-stage amplifiers with selected low-noise transistors (types 2E371, 2E3101, and 2E657). The first stage was resistive and the second was resonant. The SAW resonators were connected in a feedback loop between the output of the resonant stage and input of the resistive. A low-noise oscillator with a BAW resonator was built with a 2E642 transistors with a crystal in the feedback loop (resonator in base circuit).

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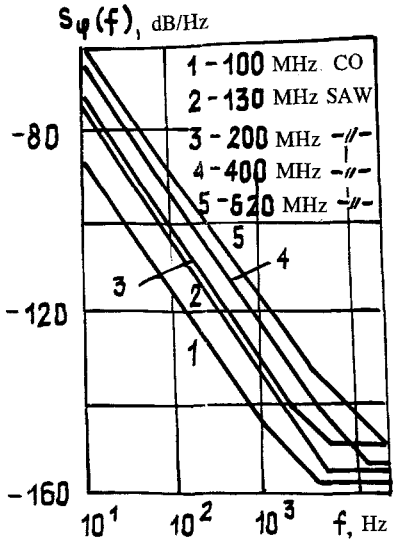

Fig. 1. Phase-noise spectra of SAW and BAW oscillators.

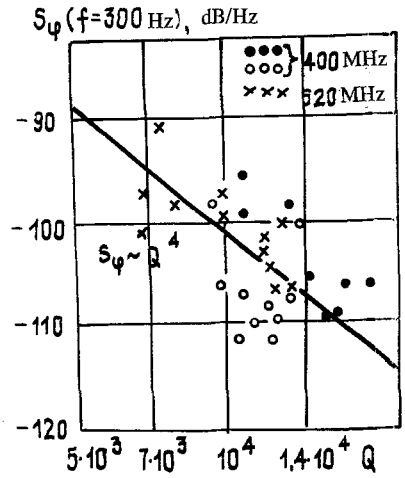

Fig. 2. Noise levels of SAW oscillators with change of resonators.

The measurement results are presented in Figs. 1-7. The phase-noise spectra of free-running oscillators operating at various frequencies are shown in Fig. 1. Curve 1 represents the noise spectrum of an oscillator with a cavity resonator with a resonant frequency of 100 MHz (at the fifth mechanical harmonic) and $Q = 10^5$. Curves 2-5 illustrate the spectra of SAW oscillators with resonators at frequencies of 130, 200, 400, and 620 MHz. The Qs of all resonators have values of $(1\text{-}1.5)\cdot 10^4$. All of the spectra reflect the noise floors of the oscillators, which are achieved by selection of the lowest-noise resonators.

In building the oscillators, the principal attention was paid to the spectral density of the phase noise, which varies as $1/f^3$ (the range of spectral frequencies in which frequency flicker noise is predominant [3]). The spectral density is not minimal at higher offset frequencies and can be reduced if necessary.

The noise levels of oscillators with SAW and cavity resonators are depicted in Figs. 2 and 3, respectively. The phase-noise spectral densities of the oscillators for a 300-Hz offset frequency are shown as functions of the unloaded Q of the corresponding resonator. For convenience of comparison, the spectral densities of all oscillators were scaled to a single carrier frequency of 400 MHz. The points, circles, and crosses represent the spectral densities of the oscillator noise for resonators of different types of different batches. It should be noted that the phase-noise spectral-density values shown in Figs. 2 and 3 were obtained by changing the resonators in the oscillators as well as in the discriminators. In the first case, the lowest-noise specimens were used in the discriminator; in the second case, in the oscillator.

As can be seen from the figures, there is a large spread of noise levels from specimen to specimen – 20 dB in the SAW oscillators and more than 30 dB in the oscillators with BAW resonators. The large spread indicates the considerable

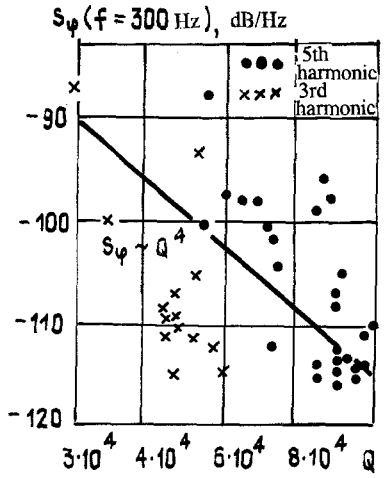

Fig. 3. Noise levels of BAW oscillators with change of resonators.

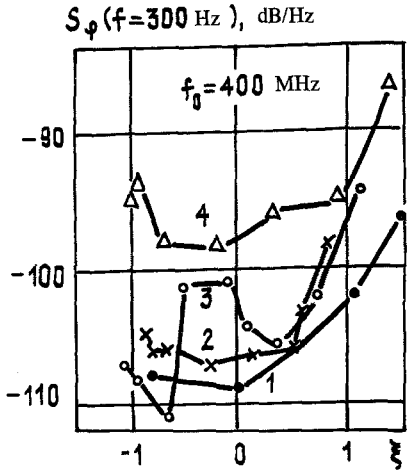

Fig. 4. Noise levels of SAW oscillators with detuning.

predominance of the effect of the internal noise of the resonators over other sources that determine fluctuations in free-running oscillators. The minimal spectral densities could be an exception. The fact of the predominance of resonator fluctuations is additionally confirmed by the change in the phase-noise spectral densities when the resonators in the discriminators are changed.

Comparison of the oscillator noise levels with the resonator Qs indicates that correlation exists between them. However, the relationship is not constant and is a function of the resonator batch. For example, for the SAW resonators the coefficient of correlation between noise level and Q is $r_{SQ} = -0.53$ (for all resonators in Fig. 2); $r_{SQ} = -0.71$ for the resonators with $f_0 = 620$ MHz; $r_{SQ} = -0.84$ for the resonators with $f_0 = 400$ MHz indicated by points; and $r_{SQ} = -0.027$ for resonators with $f_0 = 400$ MHz indicated by crosses. For the oscillators with BAW resonators, the correlation coefficient for all resonators $r_{SQ} = -0.39$; for the resonators operating at the fifth mechanical harmonic, which are indicated by points, $r_{SQ} = -0.7$; and for the resonators operating at the third harmonic, which are indicated by crosses, $r_{SQ} = -0.67$.

It has been pointed out [3] that the spectral density of the internal noise of SAW resonators is reduced approximately in proportion to Q^4. Lines reflecting the proportion $S_\varphi \propto Q^{-4}$ are provided in Figs. 2 and 3. As can be seen, the variations of the spectral densities of the noise of SAW and BAW resonators correspond to this proportion to a certain extent.

Comparison of the noise levels of the SAW and BAW resonators shows that the cavity resonators provide a lower level of phase noise by 5-7 dB when low-noise resonators are employed. However, the spread of the noise levels of the BAW resonators is greater than that of the SAW resonators, and oscillators with the worst cavity resonators can be noisier than the worst SAW oscillators.

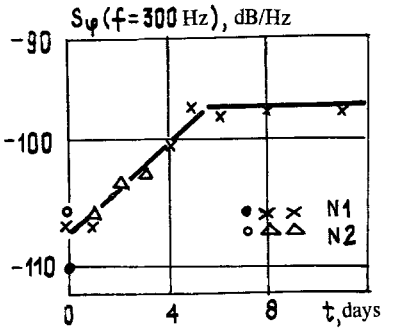

Fig. 5. Noise levels of SAW oscillators with opening of resonator cases.

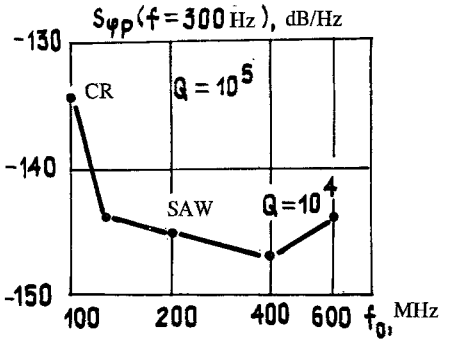

Fig. 6. Resonator phase-noise spectral density versus resonant frequency.

The large spread in the resonator noise levels is an independent problem. Determination of the causes of this spread would make it possible to correct the technology of resonator fabrication and improve quality. Some steps toward the solution of this problem have been made for SAW and BAW resonators.

The phase noise of resonators of various designs operating at various mechanical harmonics (third, fifth, and ninth) and at various frequencies. The spectral densities of the noise of resonators operating at the third and fifth harmonics are illustrated in Fig. 3. Precision resonators operating at 100 MHz at the ninth harmonic have, on the average, the same noise.

The higher-frequency resonators have higher noise levels. For example, those with a resonant frequency of 170 MHz operating at the fifth mechanical harmonic have a noise level that is approximately 15 dB higher.

All of the BAW resonators studied had the same AT cut but different constructions. Some were in vacuum containers and some where hermetically sealed. No qualitative difference in the noise levels of the different resonators was observed.

The behavior of the noise characteristics of the BAW resonators (a large spread, a rise in level with an increase in operating frequency, and independence from construction) indicate that the cause of the resonator noise is concealed in the quartz. Thinner quartz plates are subject to fabrication defects; therefore, the higher-frequency resonators have a higher noise level.

The study of SAW resonators also led to the conclusion that the quartz had the predominant effect. The phase-noise spectral density of an SAW oscillator with an operating frequency of 400 MHz for an offset frequency of 300 Hz is shown in Fig. 4 as a function of the detuning with respect to the resonant frequency of the resonator (for four specimens). The generalized detuning ($\xi = 2Q\Delta f/f_0$, where Δf is the detuning with respect to f_0) is plotted on the axis of the abscissas. As is apparent, the dependence of the spectral density on the detuning is changed considerably when the resonator is changed, and for some specimens the change is highly nonmonotonic. This behavior characteristic of the frequency dependence of the noise level of SAW resonators can be explained by the fact that various quartz defects, which are spatially separated along the reflecting lattice, which forms a standing wave, show up at different frequencies. A change of operating frequency changes the phase relationships of the waves, which are reflected from the lattice elements and added by opposed stub converters.

The state of the crystal surface exerts a considerable influence on the noise (and other) characteristics of SAW devices. This is illustrated by an experiment performed with SAW resonators with an operating frequency of 400 MHz in which the noise and other parameters were observed after the cases of the resonators were opened. The phase-noise spectral density (at

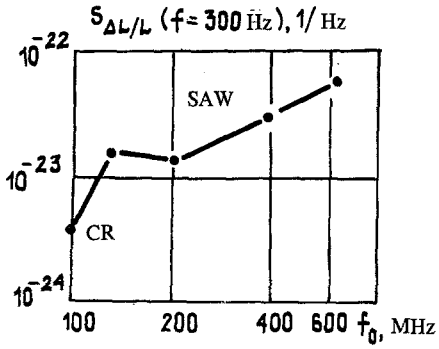

Fig. 7. Resonator equivalent-inductance-fluctuation spectral density versus resonant frequency.

an offset frequency of 300 Hz) is shown in Fig. 5 as a function of the time after opening the cases of two resonator specimens. Time in days is plotted on the axis of the abscissas. The noise level of a given type of resonator was increased during the first 5 days (by approximately 10 dB). The other parameters (resonant frequency, Q, and transmission coefficient) remained unchanged during this period. They were slightly changed after about a month (the resonant frequency fell by 10 kHz and the Q was lowered by 5%).

Kroupa and Parker [1, 3] and others have characterized the internal noise of SAW resonators by the spectral density of phase fluctuations introduced by the resonators when harmonic oscillations pass through them. This spectral density is directly measured by a phase detector in a frequency-detection circuit in which the resonator is used as a delay element. It can be calculated from the phase-noise spectral density of the oscillator $S_\varphi(f)$ if it is assumed that the latter is determined by the phase noise of the resonator $S_{\varphi p}(f)$ [5]

$$S_{\varphi p}(f) = S_\varphi(f) 4Q^2 f^2 / f_0^2.$$

The thus-converted phase-noise spectral densities of resonators with different resonant frequencies are presented in Fig. 6. The minimum spectral densities that were observed in the experiments are represented there. It follows from the graph that the phase noise introduced by the BAW quartz resonator (CR in the figure) with $Q = 10^5$ is the highest, exceeding by approximately 10 dB the phase noise of SAW resonators with $Q = 10^4$. The noise levels of SAW resonators with different resonant frequencies are practically the same.

Such a representation of resonator noise is not in good agreement with the experimental estimates of oscillator noise in Fig. 1. More-correct from the point of view of agreement with Fig. 1 is the description of resonator fluctuations through the fluctuations of their resonant frequencies or their equivalent-circuit reactive parameters (inductance or capacitance). The spectral density of fluctuations of the relative value of the equivalent inductance $S_{\Delta L/L}(f)$ is shown in Fig. 7 as a function of resonator operating frequency.

It is not difficult to show the following relationship between the spectral density $S_{\Delta L/L}(f)$ and the spectrum $S_\varphi(f)$:

$$S_{\Delta L/L}(f) = 4S_{\Delta f_0/f_0}(f) = S_\varphi(f) 4f^2/f_0^2,$$

where $S_{\Delta f_0/f_0}(f)$ is the spectral density of the relative fluctuations of oscillator frequency.

It follows from the latter representation that the noise level of the best BAW resonator is lower than that of the SAW resonators. A rise in spectral density in proportion to $f_0^{1.5}$ is observed (an exception is the SAW resonator with $f_0 = 130$ MHz); this is true of the SAW and BAW resonators.

The association of one mechanism of noise-intensity variation in SAW resonators with different frequencies and BAW resonators could be explained by a single common cause of fluctuations – for example, fluctuations of the elastic properties of the quartz.

1. SAW and BAW quartz resonators have a considerable level of parameter (resonant-frequency) fluctuation that is of the nature of flicker noise with a spectral density of nearly 1/f (in the oscillators, it appears in the form of $1/f^3$).

2. The parameter-fluctuation levels of SAW and BAW resonators have large spreads (approximately 20 dB for SAW and more than 30 dB for BAW). The phase-noise floor of oscillators with BAW resonators at 100 MHz is approximately −150 dB/Hz at an offset frequency of 1 kHz. Oscillators with SAW resonators (at frequencies of 400-600 MHz) are inferior by 5-10 dB (when the noise level is scaled to a carrier frequency of 100 MHz).

3. The cause of parameter fluctuations in both SAW and BAW resonators can most likely be found in fluctuations of the quartz parameters.

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