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MODERN REFERENCE OSCILLATORS FOR FREQUENCY SYNTHESIS

The main requirements for reference generators are considered. Modern support generators for frequency and signal synthesis systems are considered. The classification of modern reference generators is given. The main classification requirements for auto-generators are considered. Standards of frequency and time, precision quartz generators, microwave generators, reference generators on microelectromechanical resonators are considered. The use of microelectromechanical resonators and other of microelectromechanical elements is an alternative approach to miniaturization and improvement of communication equipment characteristics, simplification of heterodyne architecture, and the creation of multiband transceivers based on high-quality MEMS filters. Using MEMS technology in combination with standard semiconductor IC technology will further enhance integration, significantly reduce the size of devices, improve their characteristics. In addition, the use of MEMS in quartz frequency modulators allows you to significantly improve the basic characteristics of the device. Areas of application of this or that type of resonators as reference generators for systems of synthesis of frequencies and signals are determined. The technology of manufacturing MEMS resonators allowed to create fundamentally new structures of direct frequency synthesizers based on high-quality MEMS-resonators as the main reference generator and a set of high-quality filters designed to form the set of required frequencies. Such a synthesizer can be implemented on a single crystal of silicon, which will make it possible to reduce the cost of production of synthesizers.

Keywords: oscillator; reference oscillator; atomic standards; quartz resonators; MEMS.

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СУЧАСНІ ОПОРНІ ГЕНЕРАТОРИ ДЛЯ СИСТЕМ СИНТЕЗУ ЧАСТОТ І СИГНАЛІВ

У статті розглядаються сучасні опорні генератори для систем синтезу частот і сигналів. Наведено класифікацію сучасних опорних генераторів. Проаналізовано основні класифікаційні вимоги до таких генераторів. Розглянуто стандарти частоти і часу, прецизійні кварцові генератори, генератори НВЧ, опорні генератори на мікроелектромеханічних резонаторах (MEMS). Застосування *мікроелектромеханічних* резонаторів і інших *мікроелектромеханічних* елементів є альтернативним підходом мініатюризації і поліпшення характеристик апаратури зв'язку, спрощення архітектури гетеродинів, а також створення мультиполосних трансиверів на основі високодобротних MEMS-фільтрів. Використання MEMS-технології в комплексі зі стандартною напівпровідниковою технологією ІС дозволить в подальшому підвищити рівень інтеграції, значно зменшити габарити пристроїв, поліпшити їх характеристики. Крім того, застосування MEMS в кварцових частотних модуляторах дає можливість істотно покращити основні характеристики пристрою. *Визначено області застосування того чи іншого виду резонаторів в якості опорних генераторів для систем синтезу частот і сигналів. Запропоновано нові структурні схеми побудови прямих синтезаторів частот з реалізацією на кристалі кремнію в єдиному технологічному циклі. Технологія виготовлення MEMS резонаторів дозволила створити принципово нові структури прямих синтезаторів частоти на основі високодобротних MEMS-резонаторів в якості основного опорного генератора і набору високодобротних фільтрів, розрахованих для формування набору необхідних частот. Такий синтезатор може бути реалізований на одному кристалі кремнію, який дасть можливість здешевити виробництво синтезаторів.*

Ключові слова: автогенератор, опорні генератори, атомні стандарти, кварцові резонатори, МЕМС.

Formulation of the problem. Direct digital frequency synthesizers play an important role in modern radio electronic devices. This is provided by many significant advantages: speed of synthesizer tuning from frequency to frequency, high resolution, wide synthesized frequency band. Multilevel DDS, due to its technology, reliability, the possibility of microminiaturization and uniqueness of technical characteristics (the continuity of the phase during switching from frequency to frequency, the possibility of forming complex signals, digital control of the amplitude, frequency and phase of the output swing) have now found application in communication systems. Particularly promising is the use of DDS in radio communication systems with increased noise immunity and security [1]. To date, a number of characteristics of computational frequency synthesizers are lower than those based on PLL synthesizers. Such parameters are low indicators of short-term phase stability (jitter), the existence of harmonic components with high amplitude values in the spectrum of the synthesized signal. One of the directions for improving short-term phase stability is the use of reference generators with improved quality characteristics.

Analysis of research and publications. A lot of authors and scientific teams were engaged in the construction of highly stable reference generators [2–4]. Such generators are very different in average frequency, signal levels and relative frequency instability, which can change from 10^{-3} to 10^{-15}. Periodic oscillations of autonomous generators $u(t)$ are characterized by the average frequency, the shape of the oscillation during its period, and the fluctuations of the current phase. The stability of the frequencies of such generators is estimated by comparing their signals with variations in the secondary frequency standards. The almost harmonic oscillation of the reference oscillator can be written in the form

$$u(t) = u_0[1+\mu(t)]\sin[2\pi f_0 t + \varepsilon(t) + \varphi_0], \tag{1}$$

where U_0 and f_0 – is the amplitude and carrier frequency of the reference signal, where $\mu(t)$ and $\varepsilon(t)$ – is its amplitude and phase instabilities, is the initial phase of the oscillation. Immediately after switching on the voltages of the self-excited generators into variables, regular components are included, which determine the duration of the amplitude setting and the frequency coasting during warm-up. In a fixed temperature regime, the processes that cause amplitude and phase instabilities are random. With continuous operation, a drift of the mean frequency is possible, which is associated with the aging of the stabilizing resonator or the degradation of the vacuum in the flasks of atomic frequency standards. The Relative standard deviation (RSD) from the frequency of the standard is characterized by the error of frequency setting d_{set}. For generators with low stability, the error values drop in hundredths (percent). For generators with medium stability, indicate parts million^{-1} per million (ppm), in the case of high stability, billions (billion) (parts per billion – ppb) [4].

The nature of the phase and amplitude instabilities determines the spectral power density (SPD) of a periodic oscillation $u(t)$ at a unit resistance, concentrated near the frequency f_0 :

$$S_p(f) = 2\int_0^{\infty}[u(t)]^2 \cos 2\pi ft dt . \tag{2}$$

Nevertheless, the more correct is the characteristic of oscillations of the oscillator is its SPD of its phase instability $S_{\varphi}(F)$, where $F = |f - f_0|$ is the detuning from the nominal frequency. Phase instability is uniquely determined by the instability of the cyclic oscillation frequency

$$\Delta f(t) = \frac{1}{2\pi} \cdot \frac{d\varepsilon(t)}{dt} , \tag{3}$$

and the power spectral density of the phase deviation is related to the SPD of the frequency deviations by the relation

$$S_f(F) = F^2 S_{\varphi}(F) . \tag{4}$$

For a short time, possible phase changes, which are caused by the jitter of the signal front (jitter). Jitter is caused by amplitude and phase noise, both internal and external origin. The jitter of the signal has different characteristics depending on its causes and sources. Jitter is divided into two main categories: random (jitter – RJ) and regular (deterministic jitter – DJ).

Random jitter due to noise processes that occur in all semiconductors and components. It is assumed that this jitter is subject to the Gaussian distribution, and as such, it can never reach its maximum value in a given period of time. Thus, it is characterized by statistical values: the mean value and the standard deviation. The sources of random jitter are:

- thermal noise – associated with the flow of electrons in conductors and increases with increasing bandwidth, temperature and thermal resistance;
- shot noise – noise of electrons and holes in semiconductors, which increases depending on the bias current and the measured frequency band;
- flicker noise – noise, the spectrum of which is inversely proportional to the frequency, the so-called. pink noise;
- noise of power supply ripple;
- noise of external acoustic influences (microphone effect).
- The regular jitter is caused by the processes acting on the signal that occur in the system equipment. Systemic jitter depends on the characteristics of the digital system. Examples of sources of system jitter:
- crosstalk from synthesized signals;
- influence of dispersion upon signal propagation;
- resistance non-coordination.

The jitter is estimated from the value of the root-mean-square deviation of the phase transition moments through zero and measured in picoseconds.

It is convenient to present a general estimate of the instability of the frequencies of reference generators in the form of the standard deviation of the frequency for a certain time interval. Short-term frequency instability $\delta_{sh}(T)$ determines the relative standard deviation (RSD) for a time T of duration 1,10,100 or 1000 s. This parameter determines the contribution to frequency noise of such natural processes as the shot and thermal noise of the oscillator. The long-term instability of frequency $\delta_l(T)$ over time T lasting a day, month, year, 10 years – characterizes the effect of aging and degradation of elements.

The value of the reference oscillation frequency of the reference oscillator depends on external destabilizing factors, the main one of which is the ambient temperature. The temperature coefficient of frequency deviation (TCD) is at a nominal temperature in relative fractions of 1°C.

The oscillation form of oscillators of any design is not absolutely harmonic. The distortion characteristic of the harmonic oscillation form is the power level of the higher harmonics in $S_p(f)$ at the frequencies $2f_0$ and $3f_0$ or the power of all parasitic spectral components in a wide frequency band with respect to the power at the reference frequency.

The classification of reference generators is shown in Fig. 1.

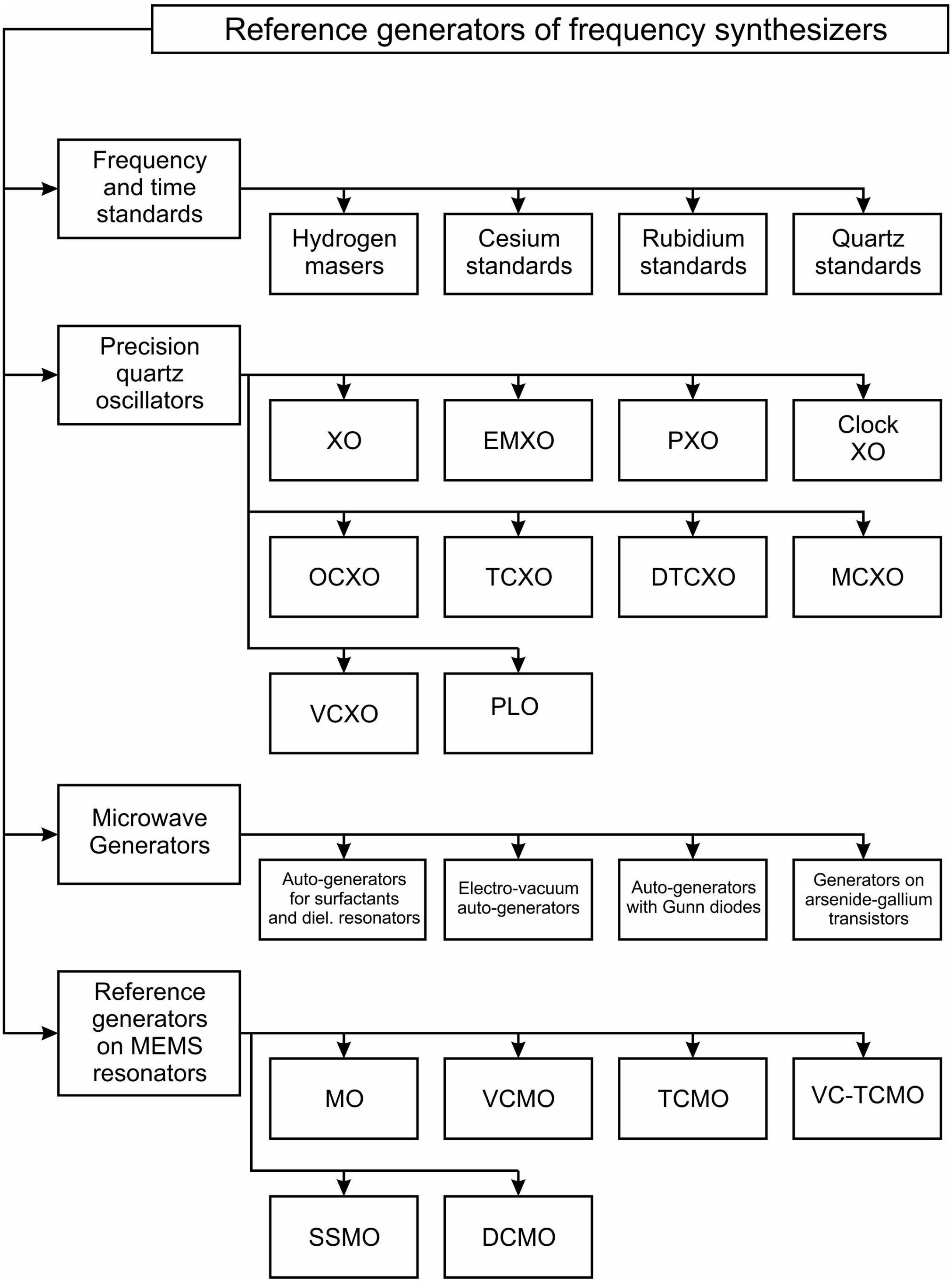

Fig. 1. Classification of reference auto-generators of frequency synthesis systems

The frequency and time standards are highly stable sources of electromagnetic signals (radio frequency range or optical ones). Frequency standards are used as secondary or working standards in metrological measurements, as well as in the production of high-precision instruments for measuring frequency and time, in radio navigation, radio astronomy and in other areas.

Quantum frequency standards are devices in which quantum transitions of particles (atoms, molecules, ions) from one energy state to another are used to accurately measure the oscillation frequency or to generate oscillations with a fairly stable frequency. Quantum frequency standards are usually divided into two classes. In active quantum frequency standards, quantum transitions of atoms and molecules directly lead to the emission of electromagnetic waves, the frequency of which serves as the standard or reference frequency. Such devices are also called quantum generators. In passive quantum frequency standards, the measured oscillation frequency of an external oscillator is compared with the frequency of oscillations corresponding to a certain quantum transition of the selected atoms, i.e. with the frequency of the spectral line.

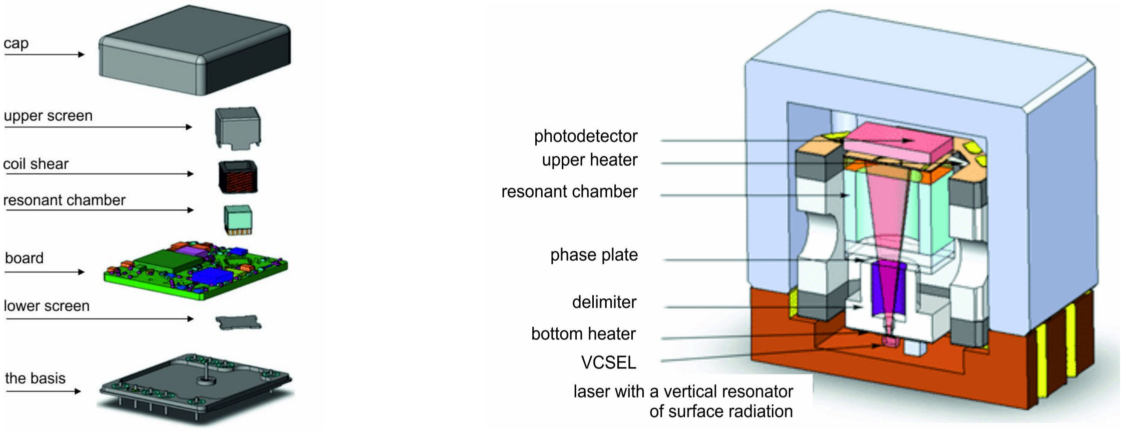

Fig. 2. The internal structure of the frequency standard of Simmetricom on the basis of caesium atoms [4]

Standards can be classified behind the material of the working body of quantum generators (hydrogen, caesium, rubidium, quartz).

The frequency and time standards do not find wide application or occupy a limited niche in frequency and signal synthesis systems mainly because of their weight and energy characteristics. As an exception, we can give an example of a reference caesium standard by Simmetricom (USA) Quantum SA.45s CSAC. This is a quantum frequency standard based on caesium atoms [4]. The internal structure of which is shown in Fig. 2.

Such a standard of frequency and time has outstanding characteristics for its size. See Table 1. However, the high cost of such a reference oscillator does not make it possible to use it in mass frequency synthesizers. Applications are limited to specialized scientific and military equipment.

Table 1

Comparative characteristics of high-precision reference generators

	TCXO	***OCXO***	***Atomic Standard***	***Atomic Standard CSAC***
Amount	0,07 cm^3	52 cm^3	122 cm^3	16 cm^3
Power at 25 ºC	20 mW	3 W	10 W	120 mW
Exit delay	731 μs	69 μs	1,7 μs	2,3 μs
Initial accuracy	$< 1\cdot10^{-6}$	$< 1\cdot10^{-7}$	$< 5\cdot10^{-11}$	$< 5\cdot10^{-11}$
Temperature coefficient	$\pm 3\cdot10^{-7}$	$\pm 3\cdot10^{-8}$	$\pm 3\cdot10^{-10}$	$\pm 1\cdot10^{-9}$
Cost	low	high	high	high

Microwave generators are used in the frequency bands from 300 MHz to 100 GHz. Stabilization of their generation frequency by quartz resonators is impossible, therefore, either the requirements for frequency stability are reduced, or other types of stabilizing resonators are used, or the means for phase synchronization of the frequency of microwave oscillations are used by frequency standards.

The quality of the reference microwave generators is estimated by additional parameters that characterize the effect of the phase of the reflection coefficient on the load and variations in the supply voltage on the frequency.

The self-excited oscillators on SAW are characterized by an increased output power and a low level of phase noise up to + 10 - + 23 dBm. So the value of the white phase noise of the modern generators is extremely low – 175 dB/Hz with the detuning of 100 kHz from the frequency of 2 GHz [5].

The use of dielectric resonators permits an increase in the output frequency to 30 GHz at a stability of 100-400 ppm. Phase noise near the reference frequency of generators of fixed frequencies with sapphire resonators on the range of 8-10 GHz and output power + 13 dBm is very low. The DRO-1000-XX series generates an internal power supply voltage regulator, means for reducing the microphone effect, and a power amplifier to the level of +13 to +25 dBm at frequencies up to 26 GHz [5]. The technique of disk dielectric resonators permits the creation of microwave generators, which exceed the stability of quartz and even atomic devices. While the use of this technique is constrained by the problem of repeatability of parameters from one copy of the resonator to another and a high manufacturing cost. Millimeter-wave mill generators of the DRO-FT-10 series use arsenide-galvanic field effect transistors with a Schottky gate (MESFET) or Gunn diodes [4].

A group of electronic components of the PLO series adjoins the reference oscillators, which serves to transfer the stability upward in frequency: multipliers of high frequency and phase locked loop (PLL) [6]. Unlike full-scale synthesizers of a grid of stable frequencies, there are no means for organizing a small step in frequency: the required output frequency is specified in the output generator with a quartz resonator. Due to this simplification of the internal structure, the contribution of these components to the phase instabilities is small.

For frequency synthesis systems and signals that are massively used in industry in the mid-frequency ranges, as a rule, high-precision quartz generators are used as self-oscillators. Auto-generators based on quartz resonators are divided into a large number of groups: Conventional crystal oscillators (Crystal oscillator – XO); Vacuum miniature (Evacuated miniature – EMXO); Precision (Precision ... – PXO); Clock (Clock XO);

thermostabilized (Oven controlled ... – OCXO); Temperature compensated ... (TCXO); with digital compensation (Digitally compensated ... – DTCXO); with microprocessor compensation (Microprocessor compensated ... – MCXO); controlled by voltage in frequency (Voltage controlled ... – VCXO); phase locked (Phase locked ... – PLO).

Auto-generators based on quartz resonators have a well-known number of advantages over other types of self-excited generators, however, they have a number of disadvantages. An important drawback in terms of their use in frequency synthesis systems and signals, there is a small frequency range. The main resonance frequency of quartz resonators does not exceed 40 MHz. Only the use of higher harmonics of a quartz resonator makes it possible to increase this range, however, the quality factor of the resonator decreases, and consequently the frequency instability of the synthesized signals increases. Another problem is the phenomenon of aging of the resonator, which is observed in the first year of operation of the resonator. Also for quartz resonators, the strong dependence of the resonator on the ambient temperature is characteristic. To combat this phenomenon, higher mechanical harmonics are used for the temperature stabilization of the fundamental frequency of oscillations [3].

Built-in digital or microprocessor thermal compensation schemes provide precise frequency stability in extended temperature range. Such MCXO circuits provide frequency instability at the level of $1 \cdot 10^{-9}$. Phase noise near the reference frequency for different models of quartz resonators is significantly different, their level may be significantly lower than for some atomic standards.

The use of quartz oscillators as a reference for frequency synthesis systems and signals is a common practice today. This is ensured by their tactical and technical characteristics and relatively low cost. Nevertheless, the constructive limitations of quartz generators do not provide an opportunity to reduce costs, improve manufacturability, and apply group and integral methods of manufacturing resonators.

An interesting alternative to quartz resonators in frequency and signal synthesis systems is auto-generators on MEMS resonators. In recent years, a fundamentally new technology for the implementation of microelectromechanical resonator devices has been widely adopted, which is a joint technology with the standard technology for fabricating IP. Thus, potentially, those devices that are currently manufactured on discrete elements can be implemented as a system on a single chip. In addition, simultaneously with the microminiaturization of the application, MEMS technology opens up new possibilities in the development of communication and signal synthesis equipment, radically changing its architecture simultaneously with the improvement of basic characteristics such as Q-factor, power consumption, noise level and bandwidth of the filter channel. See comparison table 2.

Table 2

Comparison of the parameters of the quartz resonator with the MEMS resonator

Parameter	Quartz Crystal Resonator TCXO	MEMS resonator
The size	2-5 mm	400 μm
Frequency	1-80 MHz	1-50 MHz
Quality Q ($\times 10^3$)	100-200	75-150
CMOS integration capability	Impossible	perhaps
Casing	Ceramic or metal housing	Possible plastic
Aging (for the first year)	3-5 ppm	3 ppm
Compensated temperature stability	1-10 ppm	1-10 ppm
Resistance to shock and vibration	low	high
Cost	high	low

To date, the following parameters have been achieved [2]: electromechanical resonators that operate in the frequency range 8-1800 MHz with a quality factor of 20,000...30000, respectively; controlled high-Q microcapacitors with a quality factor of several thousand in the frequency range of units of tens of megahertz, and at microwave frequencies – several hundred (for example, Q=500 at a frequency of 2 GHz); volumetric coils of inductance with Q> 10 at a frequency of up to several gigahertz.

MEMS resonators of the type and application are divided (see Fig.1) into: (MO – Oscillator) with a stability of 20-100 ppm, MEMS – voltage controlled resonators (VCMO – Voltage Controlled Oscillator) with a stability of <50 ppm, MEMS – temperature compensated resonators (TCMO – Temperature Compensated Oscillator) with a stability of 0.5-5 ppm, MEMS resonators with temperature compensation with voltage control (VC-TCMO – Voltage Controlled TCMO) with a stability of 0.5-5 ppm, MEMS – resonators with spreading (SSMO – Spread Spectrum Oscillator) with a stability of 20-100 ppm, MEMS – resonators with input frequency control (FSMO – Frequency Select Oscillator) stability of 20-100 ppm, MEMS – resonators with digital control (DCMO – Digitally Controlled Oscillator) with the stability of 0.5-100 ppm.

Micromechanical resonators can be divided into: resonators with radial, longitudinal and transverse vibrations of the resonating element. In general, the micromechanical resonator consists of immovable control electrodes, one of which is supplied with a constant control voltage, to other alternating input signals. In this case, the resonating part 1 and the signal electrodes form capacitive gaps. To operate the device, a constant control voltage is applied to the structure, and when the variable input signal acts on the electrodes, a time-varying electrostatic field is generated that causes the moving part of the structure to oscillate. The topologies of microresonators, which are realized using MEMS technology, are quite numerous. The choice of topology is determined by the frequency range and stability. The resonance frequency of a MEMS resonator depends on the properties of the material of the structure and its geometry. Differences in the design of electromechanical transducers, configurations and dimensions of the resonating element allow to vary the basic parameters of an equivalent oscillatory circuit. Such as resonance frequency, quality factor, equivalent series resistance and phase noise level.

The advantages of disk resonators are their high quality factor. The disadvantages of such resonators include a significant amount of bias voltage – about 35...70V, and a high equivalent resistance of about 30 kOhm. A promising area of application is mobile communication systems.

The disadvantage of a "fixed-beam" type resonator is a significant equivalent resistance of 4-8 kOhm. Resonators of this type operate in the range 5-17.5 MHz and are characterized by a low level of intermodulation distortion.

The combed MEMS resonator of longitudinal oscillations is the most high-quality among MEMS resonators made of polysilicon. The device is oriented to use in auto-generators with excitation at a frequency of a series resonance. The value of Q of such resonators is $Q = (50..500) \cdot 10^3$. The level of phase noise is – 168 dBm / Hz with a detuning of 5 kHz from the reference and the power of the reference is no more than –14.5 dBm. The main disadvantage of this type of resonators is the low resonance frequency $f_0 = (15..100)кГц$, which limits their field of application.

Thus, existing types of MEMS-resonators have the following characteristics: Q-factor in the range (1261...500000), equivalent resistance (1...500), TCH> (12.5×10^{-6} °C^{-1}), the bias voltage VP – (5...70) V, and are applied in a wide frequency range – (0,015-2000) MHz. The use of thermal compensation devices allows maximizing the value of the TMS of MEMS resonators to the TFC value of the quartz AT-cut resonator whose temperature coefficient (at temperatures (-73...+97) °C) is in the range (-2...2)$\times 10^{-6}$ °C^{-1}. Equivalent resistance of MEMS resonators and nonlinearity of conversion significantly exceed the analogous characteristics of high-Q quartz resonators; however, MEMS devices have much smaller dimensions and can be realized on a crystal, which makes promising their use in frequency and signal synthesis systems, in particular for creation of MEMS filters with high Q-factor, low level of introduced losses, narrow bandwidth of the channel and sharp decrease in frequency response.

The technology of manufacturing MEMS resonators allows creating fundamentally new structures of direct frequency synthesizers based on high-quality MEMS resonators as the main reference generator and a set of high-quality filters designed to form a set of necessary frequencies, see Fig.3. Such a synthesizer can be realized on a single silicon chip, which will make it possible to reduce the cost of producing synthesizers.

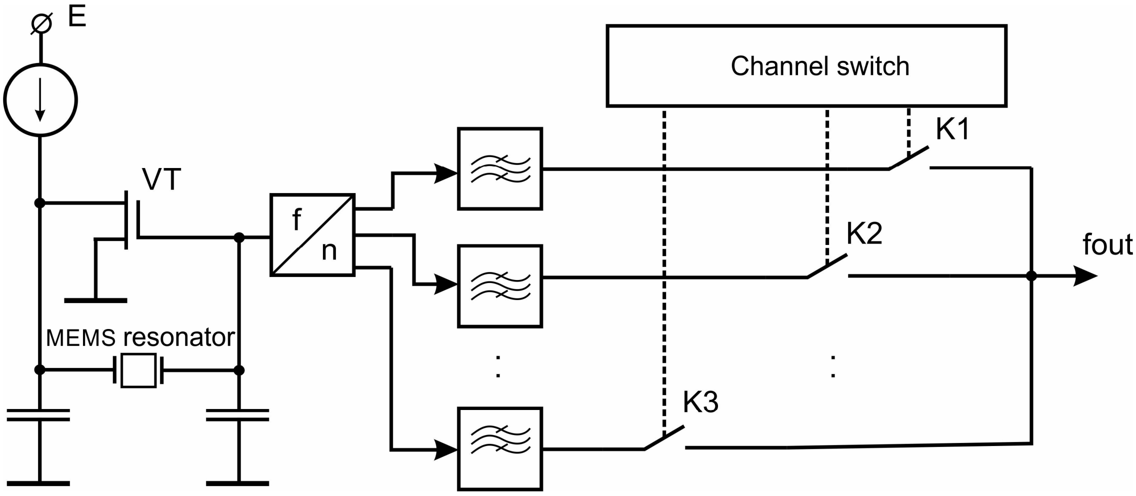

Fig. 3. Direct frequency synthesizer based on MEMS resonator and a set of filters

The synthesizer can also be realized as a set of high-quality MEMS resonators manufactured for the synthesis of known frequencies (see Fig. 4). Nevertheless, the second option has a longer time to go into operation after commutation, but has the unconditional advantage of a more accurate synthesis of reference frequencies, which is achieved by an accurate calculation of the resonators and their manufacture.

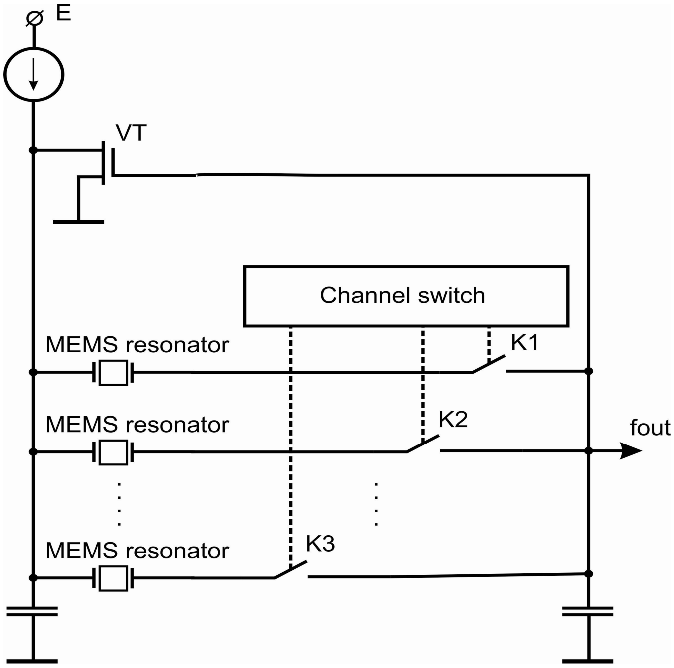

Fig. 4. Direct frequency synthesizer based on a set of high-quality MEMS resonator

Conclusions. The main requirements for reference generators are considered. Modern support generators for frequency and signal synthesis systems are considered. The classification of modern reference generators is given. The main classification requirements for auto-generators are considered. Standards of frequency and time, precision quartz generators, microwave generators, reference generators on microelectromechanical resonators are considered. Areas of application of this or that type of resonators as reference generators for systems of synthesis of frequencies and signals are determined. New structural schemes for constructing direct frequency synthesizers with the realization of silicon in a single technological cycle are proposed.

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