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Microwave Transistor Oscillators Development Based on Dielectric and Microstrip Resonators

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The paper shows the possibility of creating microwave range transistor oscillators in Ukraine based on the use of both a Dielectric Resonator (DR) and a Microstrip Metamaterial Resonator (MMR) in the form of a Split-Ring Resonator (SRR), with output oscillation parameters that are comparable to the output oscillation parameters of similar transistor oscillators currently developed by leading scientific groups in the world.

The theoretical part of the work demonstrates analytical and graphical characteristics of the S_{11} reflection coefficients of the proposed MMR in the form of an SRR and justifies the realistically achievable level of improvement in the quality factor of a resonant system consisting of two SRRs compared to the quality factors of individual SRRs.

Using the Signal Hound and Rohde & Schwarz spectrum analyzers, the output oscillation parameters of four samples of the developed transistor oscillators in the 4 GHz and 10 GHz ranges were investigated, three of which are built on the basis of a HEMT Field-Effect Transistor (FET), and the fourth - on a bipolar transistor. The output frequency of two transistor oscillators – on a FET and bipolar transistor stabilized by a DR. The output frequency of the other two transistor oscillators is stabilized by an MMR in the form of single and double SRRs respectively.

Comparison of the data obtained from the measurement results of the spectral density of phase noise for offset frequencies of 10 kHz showed that the developed transistor oscillators on a bipolar and HEMT FET stabilized by a DR are equivalent to foreign analogues of such oscillators. In turn, for offset frequencies of 100 kHz and 1000 kHz, the developed transistor oscillators stabilized by an MMR equivalent to foreign transistor oscillators stabilized by an MMR with more complex geometric configuration.

The paper may be useful for developers of microwave infocommunications devices, in particular radio-relay, tropospheric and satellite communication systems.

Keywords: dielectric resonator; microstrip resonator; metamaterial resonator; split-ring resonator; transistor oscillator; reflection coefficient

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Introduction

In modern microwave information and communication systems, harmonic oscillators are an important part of transceivers. An oscillator whose frequency is stabilized by a Dielectric Resonator (DR) belongs to the category of microwave oscillators that use a DR as a frequency stabilization element. A dielectric resonator is a sample of dielectric material with a high Q-factor (Q $>$ 1000) in the shape of a cylinder, disk, parallelepiped, etc., which is designed to function as a resonant system for devices in the centimeter and millimeter wave ranges.

The wide practical use of DR as frequency-setting circuits of microwave diode and transistor oscillators has been widely known since the 80s of the 20th century, when high-Q and temperature-stable DRs appeared [1–4]. The most widespread are transistor oscillators on the DR (DRO), built according to 2 “classical” schemes of the DR location in the feedback circuits – with “parallel” (scheme for “passing”) (Fig. 1a) and “serial” (scheme for “reflection”) (Fig. 1b) feedback. Each of these schemes includes: a resonant system in the form of a DR and microstrip lines that interact with the DR by electromagnetic coupling, an active element (transistor), a matching circuit with a load.

After the appearance in the early 2000s of Metamaterial Resonators (MR) of the SRR-type (Split-Ring Resonator), which are Microstrip Resonators (MSR) and provide a seemingly negative value of the dielectric or magnetic permeability of the resonant structure near the resonant frequency under certain conditions of their electromagnetic excitation, scientific publications appeared describing the application of these resonators in microwave oscillators [5–8]. The electrical circuits for including resonators in generator circuits are the same as in the DRO, so it is easy

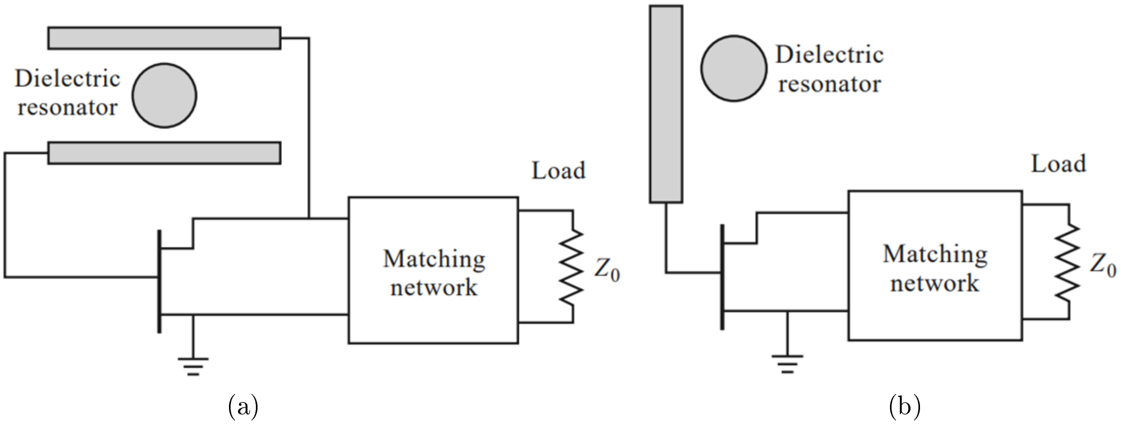


Fig. 1. DRO diagrams: a) with parallel feedback circuit; b) with serial feedback circuit

to understand that in the case of using Microstrip Metamaterial Resonator (MMR) in a circuit like Fig. 1a, a high Q-factor dependence of the S_{21} transmission coefficient of such resonator will be required, and for the circuit Fig. 1b, sharp amplitude-frequency and phase-frequency characteristics of the S_{11} reflection coefficient of the MMR will be required. However, metamaterial structures based on both microstrip and combinations of microstrip and dielectric structures do not give practically any gain in the Q-factor for a oscillator built according to a scheme with parallel feedback. That is why in works [5–8] metamaterial structures are used in oscillator schemes built with serial feedback.

Relevance. Usually, when analyzing the properties of microwave resonators, oscillators are used that differ not only in resonant systems, but also in active structures (the active part of the oscillators with different types of transistors operating in different modes), matching circuits, different resonant frequencies, types of cases, power supplies and voltage stabilizers. This publication considers the four microwave transistor oscillators samples, three of which differ from each other only in the resonator parts. This gives reason to believe that the different measured levels of the output oscillations phase noise of different transistor oscillators are explained only by the different properties of the resonant systems in their composition, which significantly increases the reliability and relevance of the measurements.

1 Formulation of the Problem

It is known that the Q-factor of the DRO resonator determines the level of phase noise fluctuations in the DRO output [9]. Therefore, the development of a DRO with a low level of phase noise is an urgent technical task for microwave communication transceivers, in particular radio relay, tropospheric and satellite transmission systems, since the phase noise created by the generator can seriously degrade the performance of such transmission systems when using modern methods of multi-position manipulation in high-speed information transmission channels. Therefore, many scientific teams of scientists and engineers around the world are making great efforts to increase the quality factor of microwave resonators, and therefore to reduce the phase noise of the DRO [4–17].

The purpose of this paper is to show the possibility of creating modern microwave transistor oscillators (DRO) in Ukraine based on the application of both DR and MMR in the form of a SRR, with output oscillation parameters that are comparable to the output oscillation parameters of similar transistor oscillators, which are currently developed by leading scientific groups in the world.

Novelty. For the first time in the paper analytical and graphical characteristics of the S_{11} reflection coefficients of microstrip metamaterial resonant structures of the SRR-type are demonstrated and the realistically achievable level of the resonant system Q-factor improvement compared to the Q-factors of its individual MMRs of SRR-type is substantiated.

2 Analysis of Research and Publications

In work [10], DRO simulation model with serial feedback on a HEMT transistor using ADS CAD was developed and investigated, which provides an output power of +10.5 dBm at operating frequency of 26 GHz and phase noise level of –95.3 dBc/Hz at a tuning of 10 kHz.

In work [11] DRO with serial feedback on a HEMT transistor with an output frequency of 7.7 GHz using AWR NI CAD was developed and simulated. Simulation results show that the phase noise is about -100 dBc/Hz at a frequency offset of 10 kHz, while the output power at 7.7 GHz is +10 dBm, and the harmonic suppression is more than 50 dB. In practical DRO measurements, its phase noise was –95 dBc/Hz at 10 kHz, while the output power is +9.4 dBm, and the harmonic suppression is more than 40 dB.

In [12], two variants of the DRO circuit implementation with parallel feedback at operating frequency of 10.25 GHz are presented. The first DRO variant has three bipolar transistors and the second – one bipolar and one Field-Effect Transistor (FET). Such multi-transistor structures introduce a negative resistance that compensates for energy losses in the DRO, which is included in the parallel feedback circuit. Experimental studies have shown that both versions of the DRO generate oscillations with a frequency of 10.25 GHz and amplitudes of 700…750 mV and 280…300 mV, respectively. The phase noise levels are –50 dB, –45 dB and –39 dB when detuned from the generation frequency by 120 kHz, 150 kHz and 180 kHz, respectively. The long-term relative frequency instability is $2.2 \cdot 10^{-6}$ 1/°C [12].

Due to its low Q-factor, the microstrip resonator is limited in reducing the level of phase noise when used as a resonator in a microwave oscillator. However, SRRs compared to conventional MSRs have the ability to provide higher Q-factors due to their narrowband (sharp) rejection characteristics and metamaterial properties. In addition, SRRs also provide simple fabrication, low radiation losses, high frequency stability, and frequency selectivity at the desired resonant frequency [1]. By increasing the number of rings in the SRR, it is possible to increase the Q-factor of the resonant system without the need to modify the existing design. SRR is a cost-effective solution for achieving highly stable and low phase noise in an microwave oscillator [13].

Split-ring resonators are widely known as metamaterial structures [14–17]. They are resonators with splits at opposite ends of each concentric ring. The ring can be round or rectangular in shape and is usually designed in an array with small gaps between them. The gaps of the inner and outer rings represent the capacitance of the resonator, while the inductance is represented by the area of both the inner and outer rings.

In the works [13, 14], samples of microwave oscillators are presented, the resonant system of which contains six identical SRRs, which are located symmetrically on both sides of the microstrip line.

The microwave oscillator consists of a FET, a SRR, a radio-frequency choke circuit, a DC bias circuit, and an output load matching circuit. A common-source series feedback topology was chosen for the microwave oscillator with SRR.

The simulation results [14] showed that resonant system with six SRRs provides a sharp characteristic of the rejection band of the S_{11} reflection coefficient and its value close to 0 dB, which allows to obtain a high Q-factor of the resonator and fulfill the necessary requirements for ensuring the generation of microwave oscillations. The transistor microwave oscillator output power is +10.6 dBm at 5.2 GHz, supply voltage of 2.0 V and power consumption current of 18 mA. Due to the sharp frequency response of the reflection coefficient S_{11}, a phase noise of about −115 dBc/Hz was achieved at 1 MHz offset frequency.

In the work [13], a FET microwave oscillator with SRR for the X-band frequency was developed using CST Microwave Studio and Agilent ADS CAD software. The resonator of such oscillator consists of six SRRs, each of which has a size of 8.15×8.15 mm^2, which provides the overall quality factor of such a resonator approximately $Q \approx 2950$. The frequency and power of the generated oscillations are 9.15 GHz and −0.65 dBm respectively, the supply voltage is 3 V. The phase noise measuring results of SRR-based oscillator at a tuning of 100 kHz are −90.51 dBc/Hz and it is lower than the phase noise of most SRR-based oscillators mentioned in [14].

In the work [8], a dual-band C-band oscillator with low phase noise using a metamaterial resonator based on Substrate-Integrated Waveguide (SIW) technology in the form of a frequency-tunable Complementary SRR (CSRR) was proposed and developed. The resonator consists of a p-i-n diode switch and a CSRR integrated into the SIW resonator. The oscillator is capable of providing two different resonant frequencies by switching between a single- and a double-ring CSRR using a p-i-n diode. A switched matching circuit is used to match each of the two states. The measurement results show that the proposed generator is capable of operating at frequencies $f = 2.675$ and 3.77 GHz with phase noise of −105.5 and −99.6 dBc/Hz, respectively, when detuned by 100 kHz relative to the carrier frequency.

3 Justification of the Oscillators Prototypes Selection. Development of the Electrical Circuit and Topology of the Oscillators

As a FET oscillators prototype, the oscillator from work [8] was chosen. As a bipolar transistor oscillator the authors proposed an oscillator with an additional matching amplifier (Fig. 2).

The choice of different types of transistor oscillators is due to the desire to consider several options for constructing oscillators using DR and MMR. The design of the printed circuit board topologies of transistor oscillators was performed using KiCad CAD software [18]. The dielectric substrate material was chosen as RT/Duroid 5880, which has a dielectric constant $\varepsilon = 2.2$, a thickness of 0.79 mm and a dielectric loss tangent $tan(\delta) = 9 \cdot 10^{-4}$.

As the DR, a cylindrical DR made of a thermostable dielectric material was used, which has the following parameters: dielectric constant $\varepsilon \approx 80$, quality

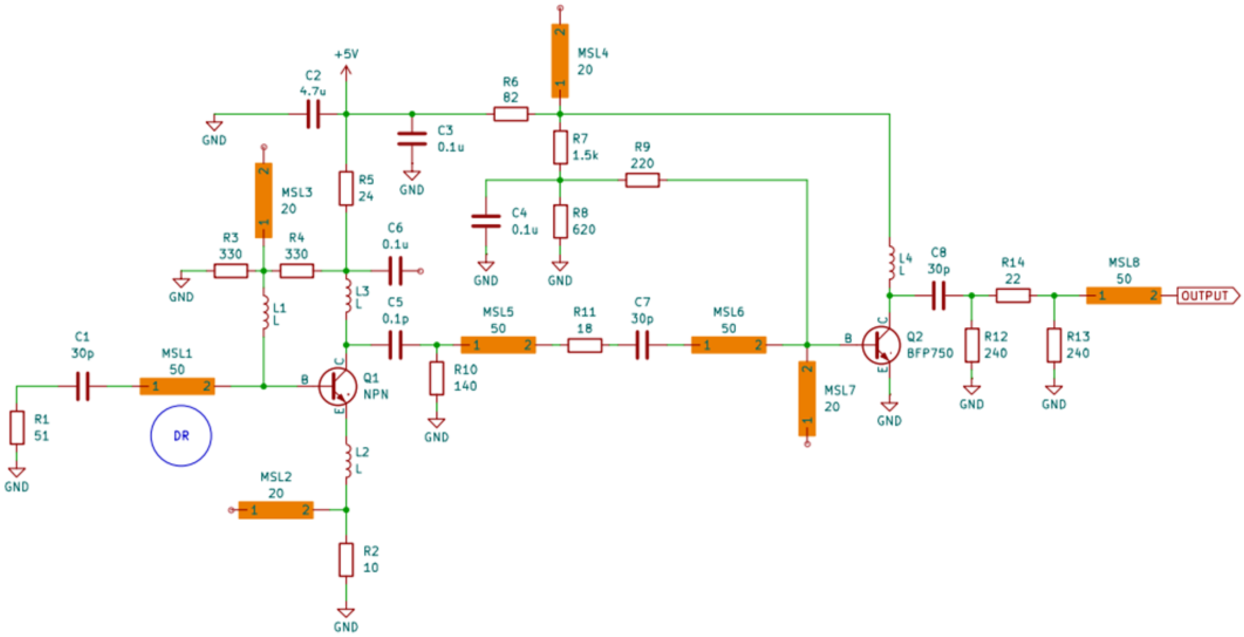


Fig. 2. Microwave transistor oscillator on bipolar transistors electrical circuit

factor $Q \approx 1700$, Temperature Coefficient of Frequency $\mathrm{TCF} = +(1.5\ldots2.5)\cdot10^{-6}$.

Two types of MSRs were used as MMRs: the first, consisting of one SRR and the second, consisting of two SRRs. The choice of such particular MSR design is due, firstly, to the simplicity of its practical implementation in the form of segments of microstrip lines, and secondly, to the possibility of obtaining a “sharp” amplitude-frequency characteristic of the S_{11} reflection coefficient from the input of such a resonator, which is confirmed by the results of theoretical calculations and practical simulation, which are presented in the works [19, 20]. In [19] it is shown that the S_{11} reflection coefficient of the MMR (Fig. 3) is described by analogy with a two-resonator system based on a DR and MSR [21] using expression:

$$S_{11} = 1 - \frac{{K_2}^*}{1+{K_2}^*} - \frac{{K_1}^*}{1+{K_1}^*}, \tag{1}$$

where

$${K_i}^* = \frac{K_i}{1+j\xi_i}, \tag{2}$$

$$K_i = \frac{Q_{0i}}{Q_{ext.i}}, \tag{3}$$

$$\xi_i = jQ_{0i}\left(\frac{\omega}{\omega_i} - \frac{\omega_i}{\omega}\right),\ \omega_i = 2\pi f_i, \tag{4}$$

Q_{0i} – unloaded Q-factor of the i-th MSR, $Q_{ext.i}$ – external Q-factor of the i-th MSR, f_i – resonant oscillation frequency of the i-th MSR.

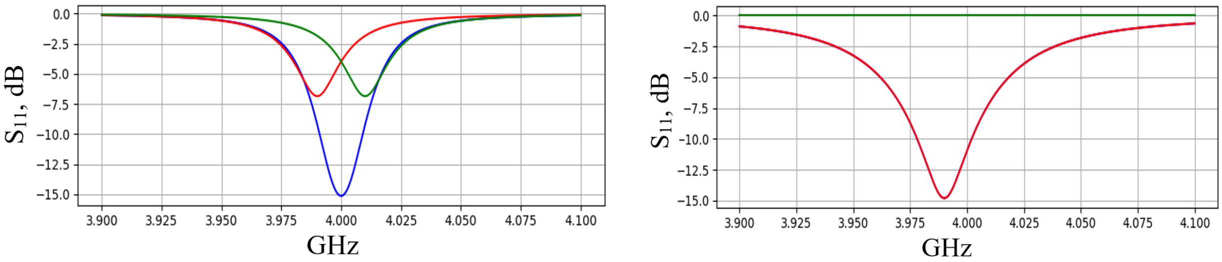
From expression (1) it is seen that the most narrowband and deep characteristic of the S_{11} reflection coefficient is achieved with weak couplings of the MSR with the transmission line, i.e. at $K_1 = K_2 \approx 1$. Fig. 3a presents multi-colored characteristics of the S_{11} reflection coefficients of individual MSRs (red and green curves) and a metamaterial resonant system consisting of two MSRs (blue curve) with quality factors $Q = 250$ (a typical value for MSR in the microwave frequency band) at $K_1 = K_2 = 1.2$.

From Fig. 3b it is clear that to achieve a similar maximum level of the S_{11} reflection coefficient (about -15 dB in our case) when using one MMR of the SRR-type, its stronger coupling with the transmission line is required, in our case $K_1 = 4.5, K_2 = 0$. Comparing the width of the resonance curves of the single-resonant structure of the SRR-type (Fig. 3b) and the metamaterial structure consisting of two MSRs of the SRR-type (Fig. 3a) at the same levels of the reflection coefficient $S_{11} = -15$ dB, we see that the blue curve in Fig. 3a is almost twice as narrow as the red curve shown in Fig. 3b, which can also be interpreted as a “doubling” of the quality factor of the metamaterial structure of two MSRs of the SRR-type compared to the single-resonator metamaterial structure of the SRR-type.

Thus, to achieve the effect of MMR Q-factor improving, which structurally consists of two MSRs of the SRR-type, in the signal reflection mode, it should be designed with coupling coefficients of individual SRRs with a transmission line close to 1.

The necessary coupling of the resonators with the line and their resonant frequencies are determined based on the expression (1) (coupling coefficients and resonant frequencies), and the physical parameters (lengths of microstrip resonators or bulk parameters of dielectric resonators) are determined by known expressions from numerous monographs, including the work [2].

HEMT is used as a GaAs FET ATF 34143 from Avago Technologies, which has a low noise figure of



(a) (b)

Fig. 3. Frequency characteristics of S_{11} the reflection coefficient for MMR consisting of: (a) two MSRs of SRR-type; (b) one MSR of SRR-type

0.4. . . 0.5 dB and a gain of about 17.5 dB. The oscillator supply voltage on the FET is selected to be 2.4 V, the power consumption is 30 mA.

SiGe bipolar transistor BFP650 was chosen to generate microwave oscillations, which has a noise figure of 0.9 dB and a gain of about 21 dB. In order to amplify the generated signal in the output amplifier SiGe bipolar transistor BFP740 was chosen which has a noise figure of 0.5 dB and a gain of about 27.5 dB. Power supply voltage on a bipolar transistor was 5 V, power consumption 180 mA.

To study different types of resonant metamaterial structures, four microwave generators with different types of resonant structures were designed: a) a FET oscillator, which stabilized by dielectric resonator (FET DRO) with an output frequency $f = 4.258$ GHz; b) a FET oscillator, which stabilized by microstrip resonator (FET OMSR) at the output frequency $f = 4.34$ GHz; c) a FET oscillator, which is stabilized by two microstrip resonators (FET O2MSR) at the output frequency $f = 4.22$ GHz; d) a oscillator on bipolar transistors (BT), which stabilized by dielectric resonator (BT DRO) with output frequency $f = 10.43$ GHz.

4 Measurement and Testing Results of the Developed Oscillators

Spectrum analyzers Signal Hound SA124B and Rohde & Schwarz FSG-13 were used to measure the spectral characteristics of the output signal generated by oscillator (output frequency, output power, phase noise spectral density). The studied oscillator were connected in turn to this analyzers.

Figure 4 presents a photograph of the topology of the developed FET DRO with the output frequency $f = 4.258$ GHz, Fig. 5a, and Fig. 5b presents the measuring results of the output signal spectrum and the phase noise level of this FET DRO, obtained using a spectrum analyzer Signal Hound SA124B. Fig. 6a and Fig. 6b presents the measurement results of the output signal spectrum and the phase noise level of the FET DRO at the output frequency $f = 4.258$ GHz, obtained using a spectrum analyzer Rohde & Schwarz FSG-13.

Figure 7 presents photo of the developed FET OMSR topology for the output frequency $f = 4.34$ GHz, and Fig. 8a, Fig. 8b – the measurement results of the output signal spectrum and the phase noise level of this FET OMSR, obtained using the Signal Hound SA124B spectrum analyzer. Fig. 9a, Fig. 9b presents the measurement results of the output signal spectrum and the phase noise level of the FET OMSR at the output frequency $f = 4.34$ GHz, obtained using a Rohde & Schwarz spectrum analyzer FSG-13.

Figure 10 presents photo of the developed FET O2MSR topology for the output frequency $f = 4.22$ GHz, and Fig. 11a, Fig. 11b – the measurement results of the output signal spectrum and the phase noise level of this FET O2MSR, obtained using the Signal Hound SA124B spectrum analyzer. Fig. 12a and Fig. 12b presents the measurement results of the output signal spectrum and the phase noise level of the FET O2MSR at the output frequency $f = 4.22$ GHz, obtained using a Rohde & Schwarz spectrum analyzer FSG-13.

Figure 13 presents photo of the developed BT DRO topology for the output frequency $f = 10.42$ GHz, and Fig. 14a, Fig. 14b – the measurement results of the output signal spectrum and the phase noise level of this BT DRO, obtained using the Signal Hound SA124B spectrum analyzer. Fig. 15a and Fig. 15b presents the measurement results of the output signal spectrum and the phase noise level of the BT DRO at the output frequency $f = 10.42$ GHz, obtained using a Rohde & Schwarz spectrum analyzer FSG-13.

5 Discussion and Evaluation of the Obtained Results

The output oscillation parameters of each of the 4 developed microwave transistor oscillators measured using Rohde & Schwarz spectrum analyzers FSG-13 are presented in Table 1.

Figure 16 shows graphs (curve №1 (4.25 GHz) – for FET DRO, curve №4 (10.42 GHz) – for BT DRO, curve №3 (4.34 GHz) – for FET OMSR, curve №2 (4.22 GHz)

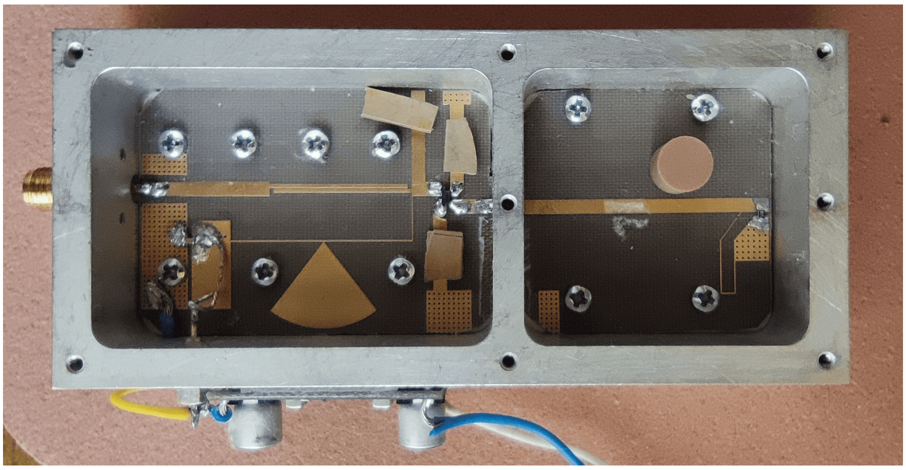
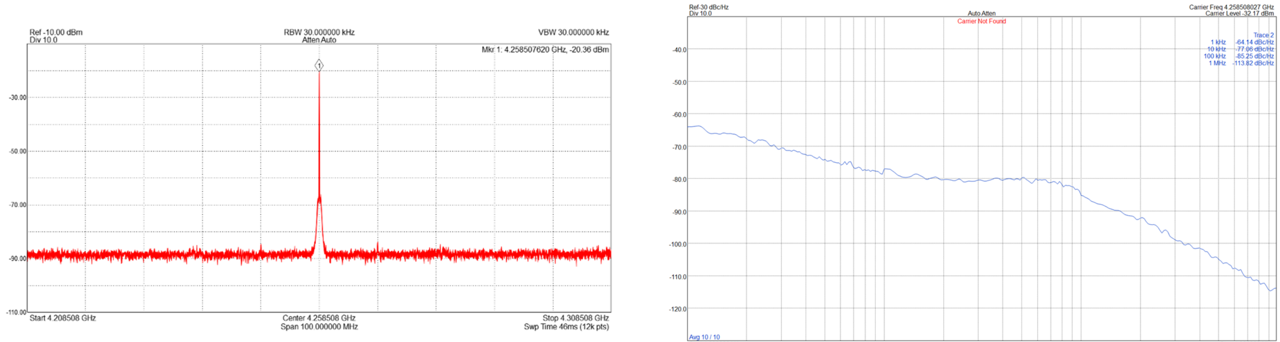


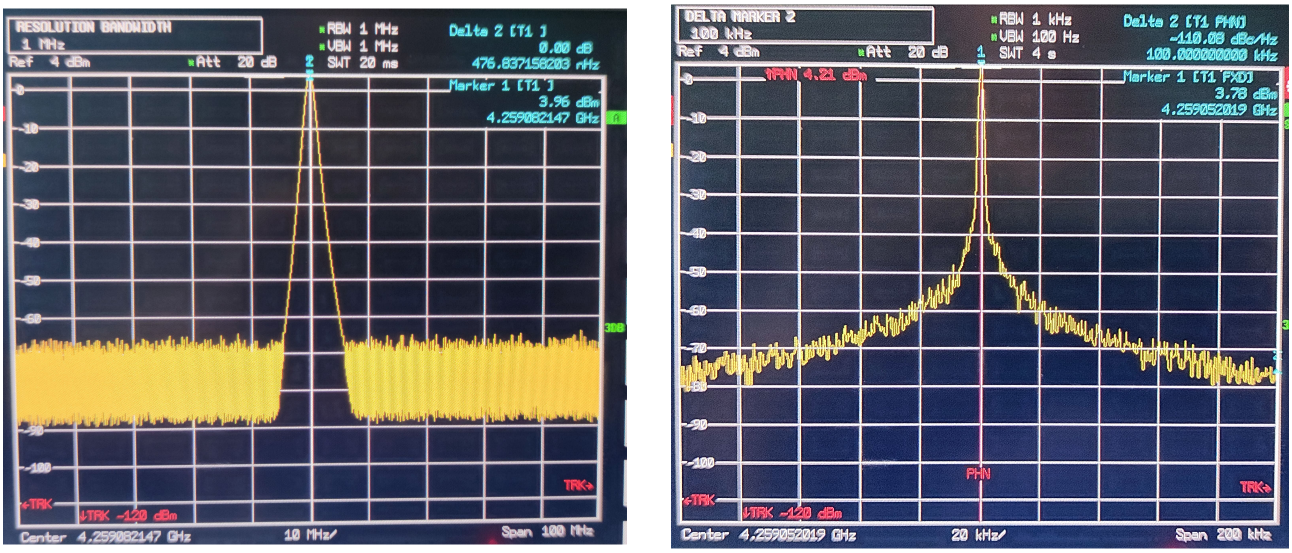
Fig. 4. Photo of FET DRO topology with output frequency $f = 4.258$ GHz



(a)

(b)

Fig. 5. Measurement results of the FET DRO output oscillation ($f = 4.258$ GHz) with using a spectrum analyzer Signal Hound SA124B: (a) oscillation spectrum; (b) oscillation phase noise



(a)

(b)

Fig. 6. Measurement results of the FET DRO output oscillation ($f = 4.258$ GHz) using a Rohde & Schwarz spectrum analyzer FSG-13: (a) oscillation spectrum; (b) phase noise level at 100 kHz offset

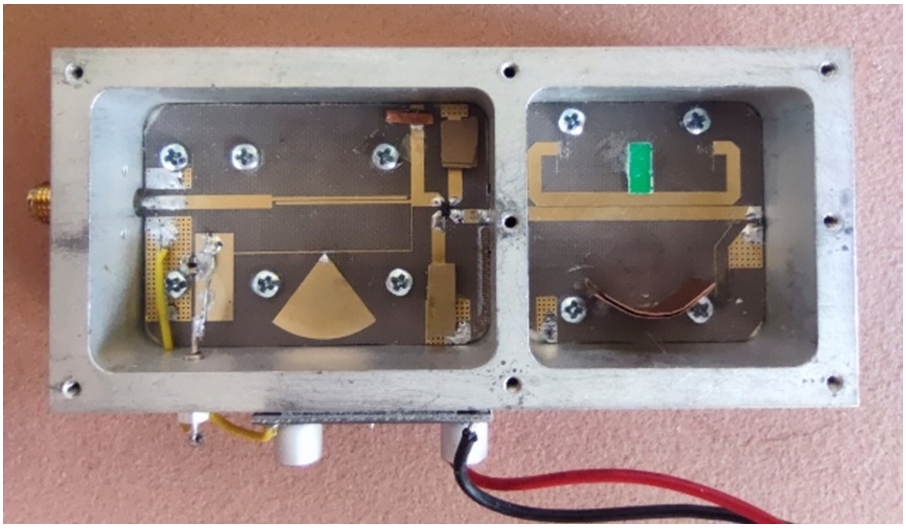
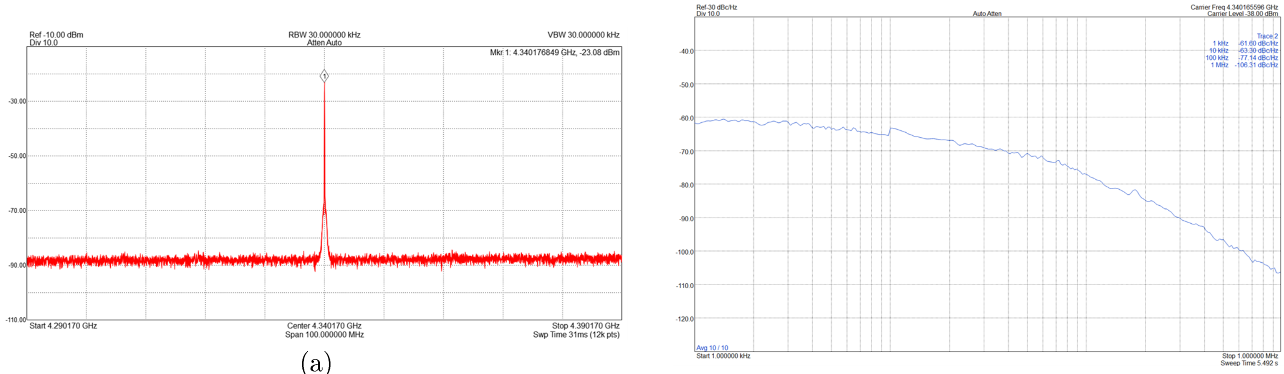


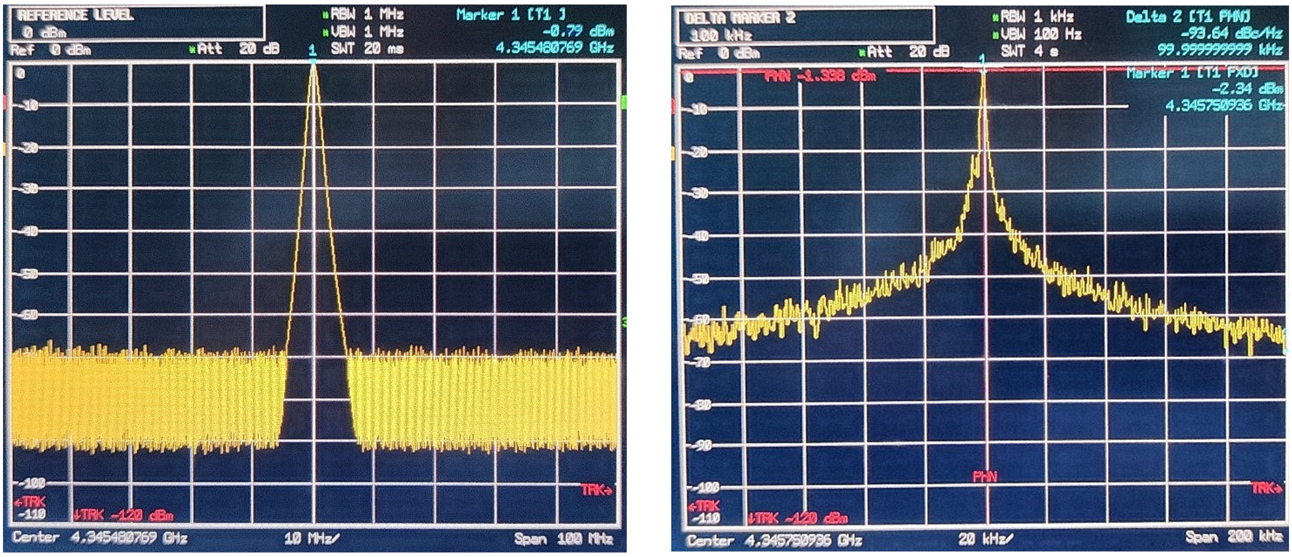
Fig. 7. Photo of FET OMSR topology with output frequency $f = 4.34$ GHz



(a)

(b)

Fig. 8. Measurement results of the FET DRO output oscillation ($f = 4.34$ GHz) with using a spectrum analyzer Signal Hound SA124B: (a) oscillation spectrum; (b) oscillation phase noise



(a)

(b)

Fig. 9. Measurement results of the FET OMSR output oscillation ($f = 4.34$ GHz) using a Rohde & Schwarz spectrum analyzer FSG-13: (a) oscillation spectrum; (b) phase noise level at 100 kHz offset

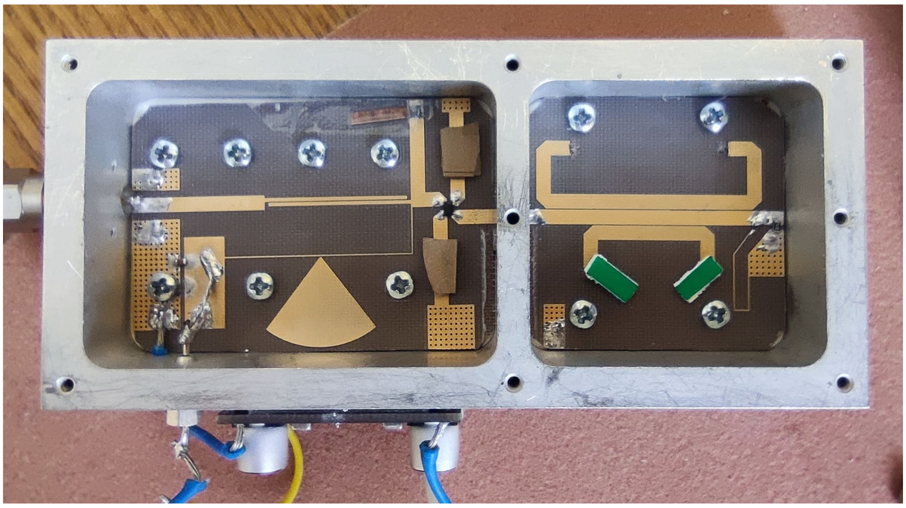
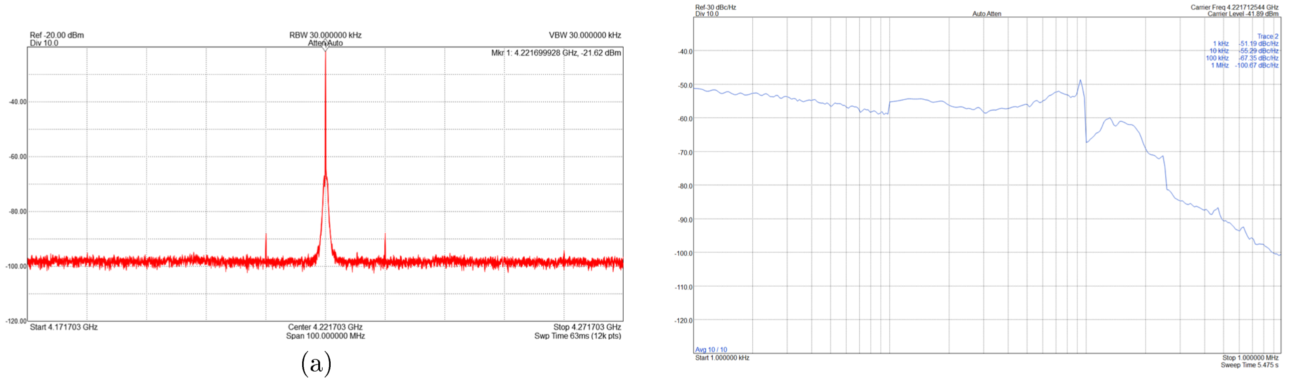


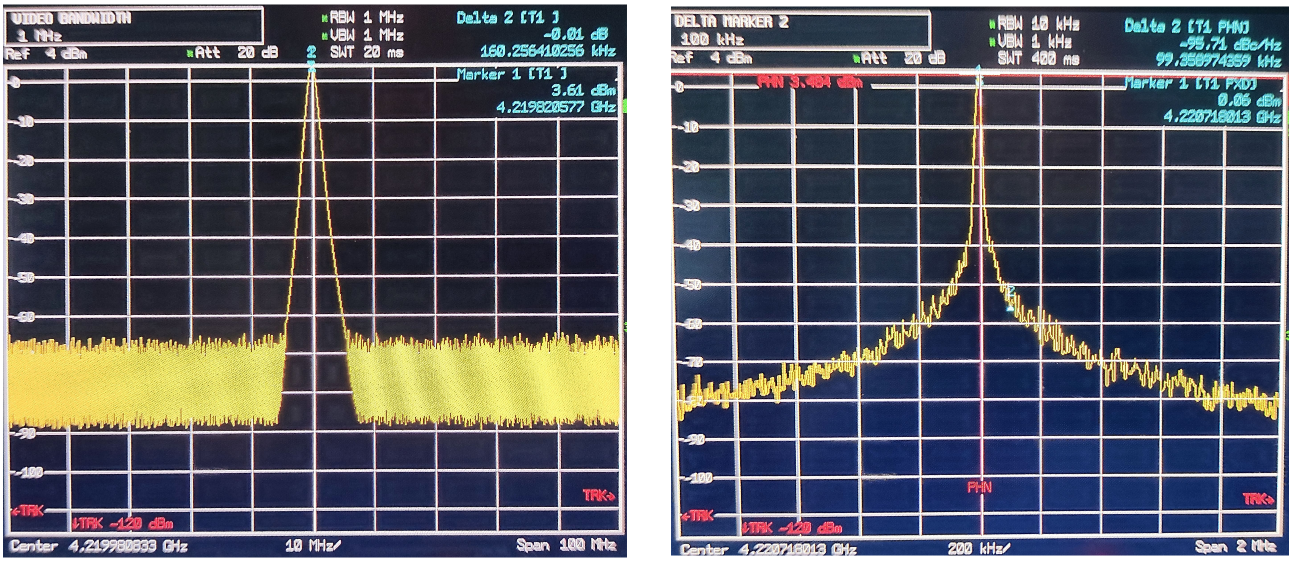
Fig. 10. Photo of FET O2MSR topology with output frequency $f = 4.22$ GHz



(a)

(b)

Fig. 11. Measurement results of the FET O2MSR output oscillation ($f = 4.22$ GHz) with using a spectrum analyzer Signal Hound SA124B: (a) oscillation spectrum; (b) oscillation phase noise



(a)

(b)

Fig. 12. Measurement results of the FET O2MSR output oscillation ($f = 4.22$ GHz) using a Rohde & Schwarz spectrum analyzer FSG-13: (a) oscillation spectrum; (b) phase noise level at 100 kHz offset

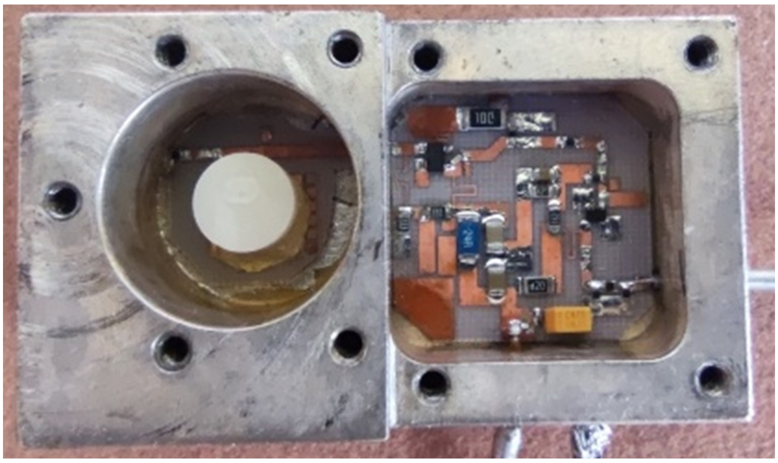
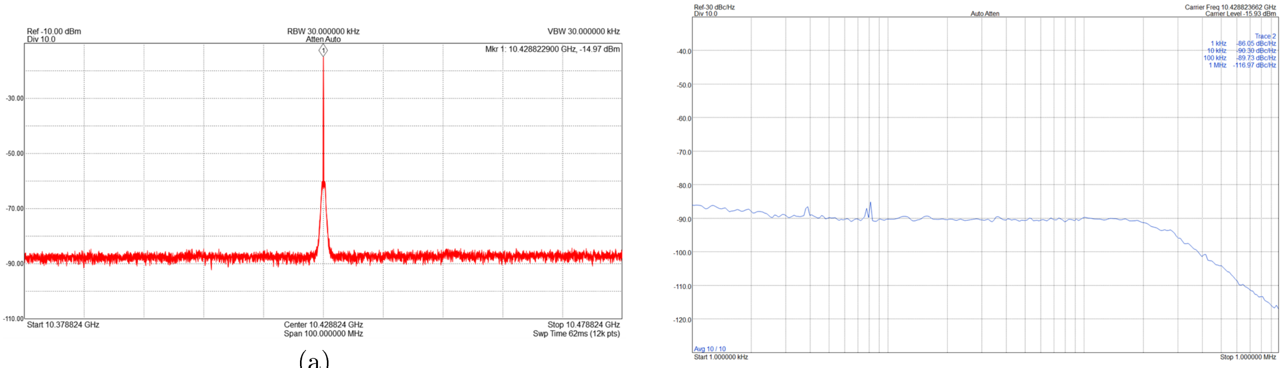
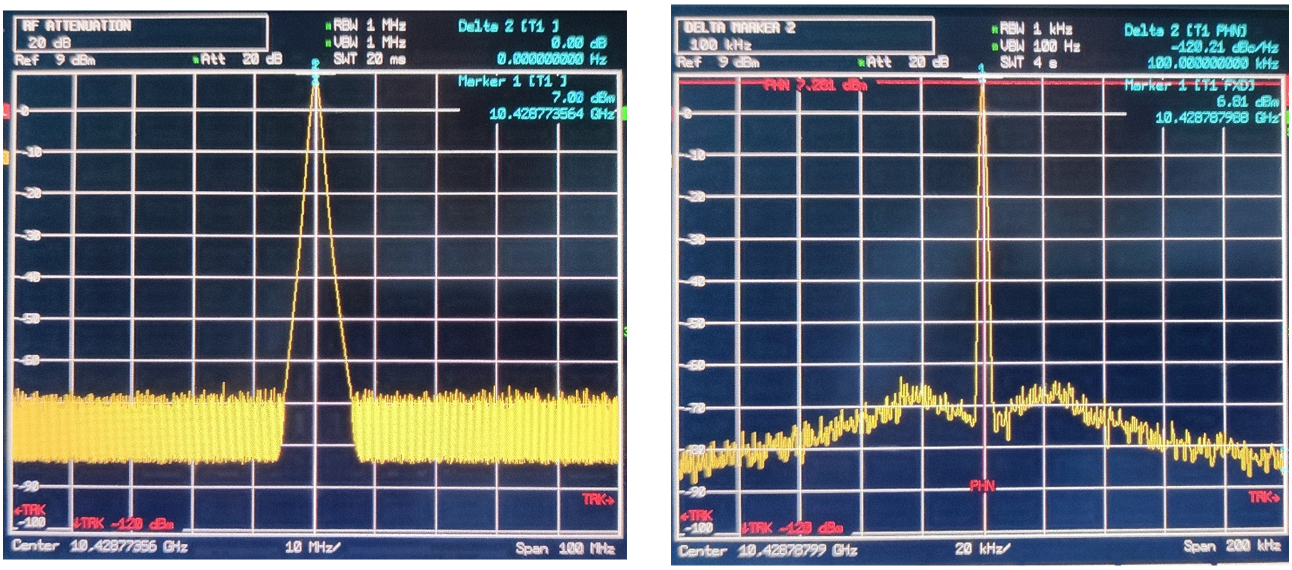


Fig. 13. Photo of BT DRO topology with output frequency $f = 10.42$ GHz



(a) (b)

Fig. 14. Measurement results of the BT DRO output oscillation (f =10.42 GHz) with using a spectrum analyzer Signal Hound SA124B: (a) oscillation spectrum; (b) oscillation phase noise



(a) (b)

Fig. 15. Measurement results of the BT DRO output oscillation (f = 10.42 GHz) using a Rohde & Schwarz spectrum analyzer FSG-13: (a) oscillation spectrum; (b) phase noise level at 100 kHz offset

– FET O2MSR) of the phase noise spectral density of the four developed microwave transistor oscillators, which are built on the basis of the data presented in Table 1. It can be seen from Fig. 16 that the best result in terms of obtaining the phase noise lowest level of is given by FET DRO and BT DRO. Microwave oscillators based on single and double MSR have the highest level of phase noise, which is caused, first of all, by the lower value of the MSRs Q-factor compared to the DR Q-factors.

As can be seen from Fig. 16, the obtained phase noise level measurements for BT DRO are better than the phase noise level for FET DRO, FET OMSR and FET O2MSR. Therefore, the next step in improving the noise characteristics of oscillators with MSR will be the transition to using BTs instead of FETs.

Table 2 shows the output oscillation parameters of transistor oscillators developed by various scientific teams. Comparison of the data in Table 1 with the data in Table 2 for 10 kHz offset frequency shows that the developed FET DRO and BT DRO are equal to foreign analogues of transistor oscillators, and for offset frequencies of 100 kHz and 1000 kHz, the developed FET OMSR and FET O2MSR are equal to foreign analogues of transistor oscillators stabilized by MMR.

Conclusions and Recommendations

As can be seen from the measurements results (Fig. 16), the oscillator with two microstrip resonators (FET O2MSR) is characterized by phase noise level, which is almost the same as that of the FET OMSR.

As shown above, according to the expression (1), to achieve the improving effect of the MMR Q-factor, which structurally consists of two MSRs of the CSRR-type, in the signal rejection mode, it should be designed in accordance with the coupling coefficients of individual MSRs with a transmission line close to $K_1 = K_2 \approx 1$. Unfortunately, the metamaterial resonator designed from two MSRs of the CSRR-type, which is used in the FET O2MSR (Fig. 10), does not meet this requirement. Therefore, there is not a significant improvement in the phase noise of the FET OSMR and FET O2MSR compared to the FET DRO and BT DRO. At this stage of the oscillators design, it has not yet been possible to achieve this.

However, a comparison of the output oscillations measurement results of the developed microwave transistor oscillators (Table 1) with the measurement results of the transistor oscillators designed by the other scientific teams shows (Table 2) that the developed microwave transistor oscillators prototypes in terms of the phase noise level are equal to foreign transistor oscillator prototypes both in the case of using DR and MMR based on the CSRR as the resonant system.

The next step in the microwave oscillators noise characteristics improving will be the application of bipolar transistors instead of field-effect transistors.

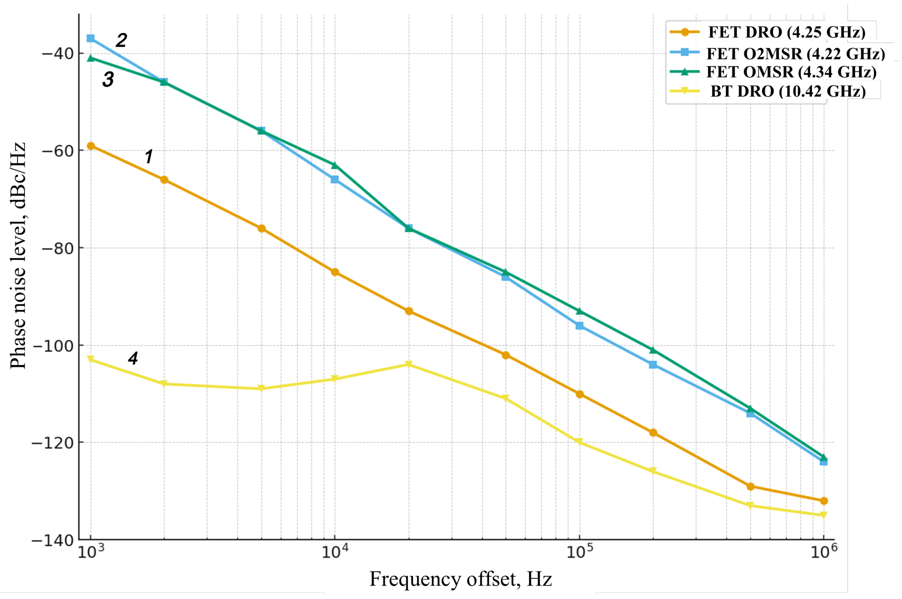


Fig. 16. Microwave oscillators phase noise level measured by using Rohde & Schwarz spectrum analyzer FSG-13

Табл. 1 Output oscillation parameters of microwave transistor generators developed by various scientific teams

Oscillator type	**FET DRO**	**FET OMSR**	**FET O2MSR**	**BT DRO**
Output carrier frequency, GHz	4.25	4.34	4.22	10.42
Output power, dBm	+3.96	−0.8	+3.61	+7
Frequency offset from the carrier	**Phase noise spectral density, dBc/Hz**			
1 kHz	−59	−41	−37	−103
2 kHz	−66	−46	−46	−108
5 kHz	−76	−56	−56	−109
10 kHz	−85	−63	−66	−107
20 kHz	−93	−76	−76	−104
50 kHz	−102	−85	−86	−111
100 kHz	−110	−93	−96	−120
200 kHz	−118	−101	−104	−126
500 kHz	−129	−113	−114	−133
1 MHz	−132	−123	−124	−135

Табл. 2 Output oscillation parameters of microwave transistor generators developed by various scientific teams

Publication	**Oscillator output frequency, GHz**	**Output power, dBm**	**Phase noise, dBc/Hz**	**Frequency offset, kHz**	**Resonator type**
[10]	26	+10.5	−95.3	10	DR
[11]	7.7	+9.4	−95.0	10	DR
[12]	10.25	300 mV	−50	120	DR
[14]	5.2	+10.6	−115.0	1000	MMR
[13]	9.15	−0.65	−90.5	100	MMR
[8]	2.67, 3.77	+5.33, +10.83	−105.0, −99.63	100	MMR

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Розроблення транзисторних генераторів мікрохвильового діапазону на основі діелектричних та мікросмужкових резонаторів

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У статті показана можливість створення в Україні транзисторних генераторів мікрохвильового діапазону на основі використання як діелектричного резонатора, так й мікросмужкового метаматеріального резонатора (ММР) у вигляді розрізного кільцевого резонатора (РКР), з параметрами вихідних коливань, що є порівняними з параметрами вихідних коливань аналогічних транзисторних генераторів, які на поточний момент часу розроблені провідними науковими групами світу.

У теоретичній частині роботи продемонстровано аналітичні та графічні характеристики коефіцієнтів відбивання S_{11}, запропоновано ММР у вигляді РКР та обґрунтовано реально досяжний рівень підвищення добротності резонансної системи, що складається з двох РКР, порівняно з добротностями окремих РКР.

За допомогою аналізаторів спектра Signal Hound та Rohde & Schwarz досліджено параметри вихідних коливань чотирьох зразків розроблених транзисторних генераторів діапазонів 4 та 10 ГГц, три з яких побудовано на базі польового транзистора, а четвертий – на біполярному транзисторі. Вихідна частота двох транзисторних генераторів – на польовому і біполярному транзисторі стабілізована діелектричним резонатором (ДР). Вихідна частота двох інших транзисторних генераторів стабілізована ММР у вигляді одного та двох РКР.

Порівняння даних отриманих результатів вимірювання спектральної щільності фазових шумів для частот відстройки 10 кГц показали, що розроблені транзисторні генератори на біполярному та HEMT польовому транзисторі, що стабілізовані ДР, не поступаються зарубіжним аналогам таких генераторів. В свою чергу, для частот відстройки 100 кГц та 1000 кГц розроблені транзисторні генератори, що стабілізовані ММР, не поступаються зарубіжним транзисторним генераторам, що стабілізовані ММР більш складної геометричної конфігурації.

Стаття може бути корисною для розробників пристроїв інфокомунікацій мікрохвильового діапазону, зокрема систем радіорелейного, тропоферного та супутникового зв'язку.

Ключові слова: діелектричний резонатор; мікросмужковий резонатор; метаматеріальний резонатор; розрізний кільцевий резонатор; транзисторний генератор; коефіцієнт відбивання