The Investigation of Filters with Wide Stop Band, Based on Electromagnetic Crystals of Microstrip Resonators 2D Disposition

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Abstract – **Microstrip bandpass filters to the 6th order, based on 2D electromagnetic crystals were studied. Their appliance in structures of irregular resonators with originally convolved and earthed on its base with strip conductors enables the implementation of filters building multiple versions, including of high frequency-selective properties. The good conformance of the calculated characteristics in comparison with the received characteristics on experimentally made model of microwave device is shown.**

Index Terms – **Microstrip filter, electromagnetic crystal.**

I. Introduction

DURING the development and researches of the frequency-selective microwave devices new construction [1], including microstrip bandpass filters, engineers traditionally try to improve their selective properties: to increase the rectangularity of an amplitude-frequency characteristics (AFCs) and simultaneously to reinforce microwave power suppression out of the bandpass (BP), as also to essentially widen the high-frequency stop band [2]. Herewith, having low cost-price, microstrip devices are more technological efficient in the manufacturing as compared with other microwave constructions.

Nowadays filters developers proposed several constructive approaches designed to the stop band widening. One of them is the usage of the multi-conductor microstrip resonators [3] within the bandpass filters implementation. In such constructions the connection between resonators at frequencies of higher mode oscillations is far less than at frequencies of the first working mode. It can be explained by the fact that at the frequency of the first resonance the high-frequency currents in all resonator conductors are co-phased, and on higher resonances in some or all conductors, depending on oscillation mode number, are anti-phased.

Herewith, their obvious disadvantage is the high definition, which is demanded during the strip conductor portions manufacturing as also gaps between them. As, for instance, in the 4th order filter, implemented on the inter-digital microstrip resonators with seven elements in each chain, minimal gaps between strip conductors are no more than 20 μm [3]. Adjusted with relative bandpass width $\Delta f/f_0 = 10\%$, the selective device has high-frequency stop band ~$3f_0$ (where f_0 is the central frequency BP) with the power suppression on its frequency not less than 50 dB. However, double bandpass expansion to $6f_0$ in the similar microstrip filter but of the relative bandpass width $\Delta f/f_0 = 20\%$, demands the further gap reduction approximately to 18 times. In this case the claimed power suppression reaches not less than 40 dB.

Another constructive approach is the usage of irregular co-directional or counter-directional resonators (see Fig.1a) with earthed on its base narrow portions of strip conductors [2,4] in one-dimensional microstrip selective structures. Such constructive approach also enables the implementation of bandpass filters with expanded high-frequency stop bands to $2.8f_0$, simultaneously with the strong microwave power suppression on their frequencies, for example, about 70 dB for the four-chained filter of the bandpass width $\Delta f/f_0 = 20\%$ with the minimal gap between strip conductors of 300 μm. For being objective we need to notice that such microwave devices are not that miniature. Moreover, they need significant growth of the one-dimensional chains number.

It is clear that microstrip bandpass filters, implemented within above mentioned approaches have numerous advantages, but also have disadvantages, that is why the researches, aimed to their frequency-selective properties improvement and manufacturability increment is the important and vital task of the radiotechnics.

II. Problem Definition

In the present article it is proposed to research the bandpass filters based on electromagnetic crystals with periodically disposed in two spatial coordinates microstrip resonators, electromagnetically collaborating with each other.

For achieving this purpose the following problems must be sold:

- transforming without frequency-selective properties deterioration the known microstrip resonator with the wide stop band [2,4] for the perspective 2D structures designing on its basis;
- 3D models developing of the of examined microstrip resonators and bandpass filters on their basis for their further electrodynamic numerical analysis and «manual» parametric synthesis with the stated electric characteristics;
- comparing the forth-order filters synthesized AFCs on the basis of electromagnetic crystals with 2D and 1D disposition of microstrip resonators;

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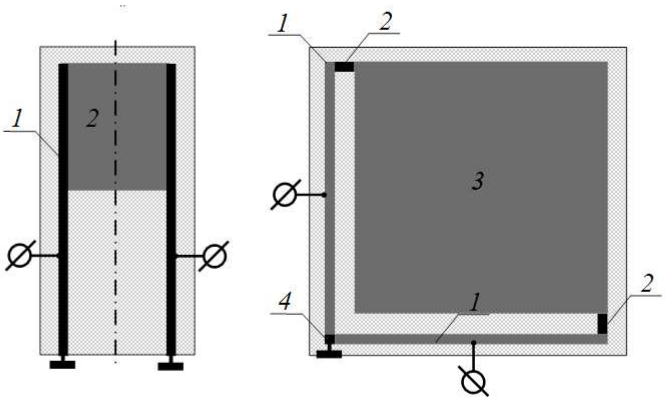
- examination of frequency-selective properties of various microstrip bandpass sixth-order filters on the basis of 2D crystal: sized 3×2, with the vertical lines bias on the crystalline lattice period, with the defects of missing resonators;
- showing of the fact that during the coordinated electromagnetic cooperation of the irregular resonators in the space can be implemented the bandpass filters of various orders of high frequency-selective properties, including of the widened stop band;
- checking the accuracy of the electrodynamic numerical analysis of the microstrip structure 3D model, comparing the calculated characteristics of the filter of the wide stop band with the measured on the experimental sample ones.

III. THEORY

Perspective irregular microstrip resonator (Fig.1a) of the wide stop band, as it is known from the works [2,4] nominally consists of three parts: disposed on one side of dielectric plate two narrow parallel strip conductors portions *1*, earthed on base from the free ends side, linked with each other by the strip conductor portion *2*.



a b

Fig. 1. Topology of the strip conductors (black or gray) of microstrip resonators with wide stop band.

As it was mentioned before, one of the main disadvantages of bandpass filters, implemented on the base of such resonator is a big size, as of the significant area of dielectric substrate free of metallization.

There are different approaches aimed to such resonator diminutiveness increase, however their main disadvantage is the significant high-frequency stop band reduction, and, consequently, filters frequency-selective properties decrement.

A brand new, original solution is the «spatial» rollup of the strip conductors portions *2-1* followed by free portions ends connection through the common earthing *4* on their base (Fig.1b). The last-mentioned could be implemented as the via hole in the dielectric substrate filled with the conductive material.

The investigation of examined resonators frequency-selective properties, as also bandpass filters on their base, was pursued on the developed 3D models of such microstrip devices which are used later for the electrodynamic numerical analysis. There were used equal substrates with the permittivity $\varepsilon = 9.8$ and thickness $h = 1$ mm (material – «polikor») for the objective devices characteristics comparison. There were also recorded the bandpass central frequency $f_0 \approx 1.0$ GHz and BP relative width – $\Delta f/f_0 = 20\%$.

In this case the device adjustment was executed by «manual» parametric synthesis with the selection of the strip conductor portions topology geometrical sizes, i.e. length, width and gaps of regular areas, specified on figures by positions numbers.

Calculated AFCs (Fig.2) of initial and «spatially» rolled up microstrip resonators at low frequencies are almost completely coincide, and the stop band width distinguishes insignificantly at high frequencies, that brings us to the conclusion about transformed resonator characteristics saving.

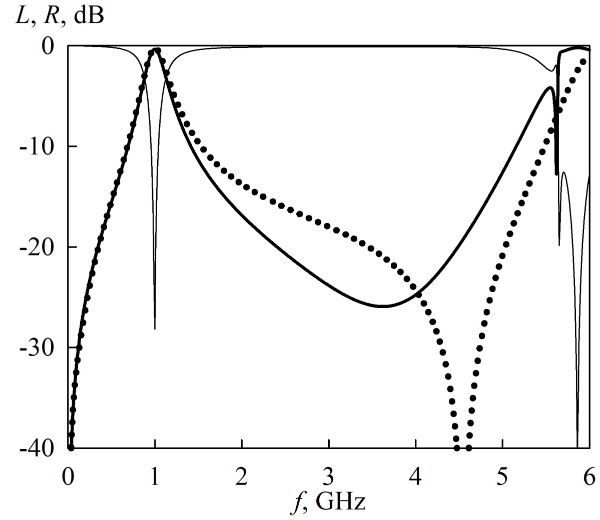


Fig. 2. AFCs of the initial resonator (points) and transformed resonator (lines).

It can be seen that the bandpass is formed by one lowest oscillations mode only, the transition to the multimode resonator behavior increases the construction diminutiveness, but is attended by significant high-frequency stop band extension reduction, implemented by means of shock-wave drags lines portions large leap.

It is significant that the resonator of «spatially» rolled up conductors portions is much more diminutive than the initial one (Tab.I), the area of the first one without conductors shifts from substrate bounds is ~ 138 mm^2, the second ~ 85 mm^2.

TABLE I
THE RESONATORS STRIP CONDUCTORS PORTIONS GEOMETRICAL SIZES

Resonator	Portion position in Fig.	Conductor portion sizes, mm	Note
Fig.1a	*1*	18.60 × 0.35	Earthed
	2	8.20 × 6.70	
Fig.1b	*1*	8.90 × 0.30	
	2	0.65 × 0.30	
	3	8.25 × 8.25	
	4	0.30 × 0.30	Earthed (all area through a substrate on base)

The presence of several options of constructions building in the new resonator significantly differs from the only construction building option in the initial resonator.

We will take a close look at the designing opportunity of proposed filters on the basis of the electromagnetic crystal of precise size, for instance, 2×2. There are four main versions of transformed resonators disposition in the construction.

In the first version the narrow inductive areas of all resonators are located around the substrate perimeter at the distance *h* from its bounds. In this case the capacitive elements, almost square strip portions, are located in the substrate center. In this structure the capacitive interaction between all resonators prevails and the circulating wave resonances appear there, destroying the BP. This prevents to implement filters of high electric characteristics.

In the second version of resonators disposition around the substrate perimeter the capacitive elements are orientated, and the inductive ones – inside. In this structure also circulating wave resonances appear, destroying the bandpass.

In the next version of electromagnetic crystal designing, the combination couplings were organized between resonators. There is the strip conductors filter topology on the Fig.3a, implemented with mainly inductive coupling between resonators of different ranks, and with capacitive one – in the same rank. In this case, earthed through the substrate on its base, portions *5* and *7* are more technologically efficient connected with each other by the narrow strip conductor and with only one earthing left.

The amplitude-frequency characteristic of the bandpass filter based on such 2D crystal is represented in Fig.4 by points. There is widened high-frequency stop band $2.7f_0$, measured by the -30 dB level, as also the bandpass low-frequency slope high steepness by virtue of the existing attenuation pole in the low-frequency area. In this case, there is the strong non-uniformity of the microwave power passage on the bandpass frequencies.

We will show that it because of resonances of the circulating wave.

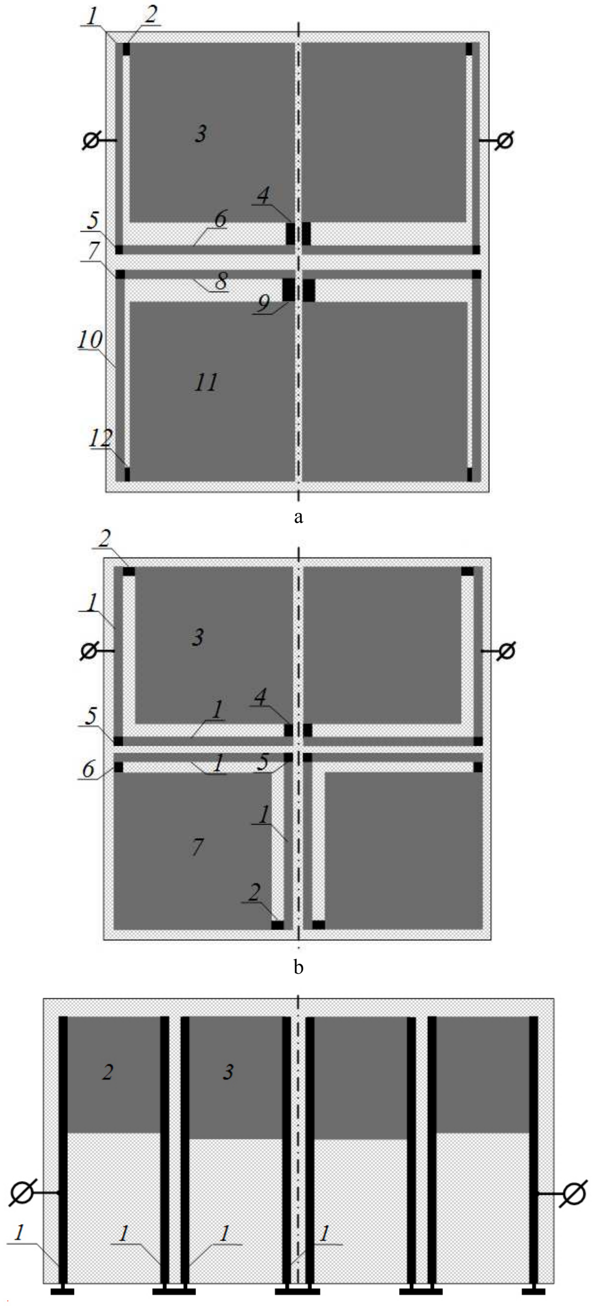


Fig. 3. Topology of the strip conductors portions of 4th order microstrip filters.

We will denote the whole incoming to the ingoing port power by P_{in}, the part of which P_{out} passes through the structure and reaches the outgoing port, the remaining power due to the energy conservation rule must be either reflected P_{ref} to the microwave highway backwards or absorbed and scattered P_{abs} structure:

$$P_{in} = P_{out} + P_{ref} + P_{abs},$$

or

$$1 = k_{out} + k_{ref} + k_{abs},$$

where the dimensionless relation

$$k_{out} = \frac{P_{out}}{P_{in}}$$

is passing coefficient,

$$k_{ref} = \frac{P_{ref}}{P_{in}}$$

is reflection coefficient,

$$k_{abs} = \frac{P_{abs}}{P_{in}}$$

is absorption coefficient.

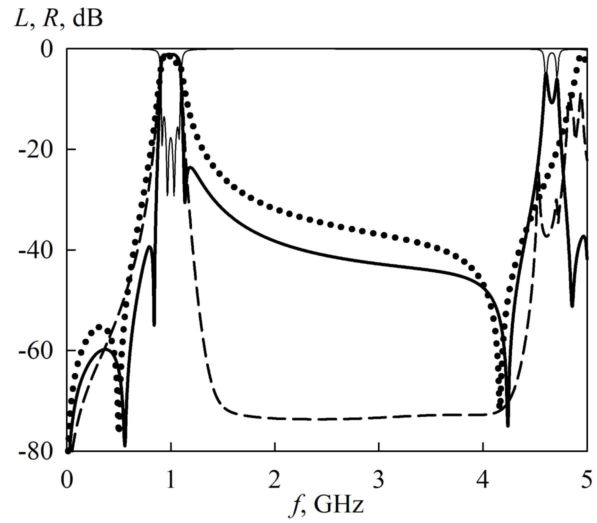


Fig. 4. Synthesized AFCs of 4[th] orders filters. Points – used the topology of conductors presented in Fig.3a, solid lines – in Fig.3b, dashed lines – in Fig.3c.

The absorption coefficient frequency dependence, calculated in percentage using the abovementioned formulae, is represented in Fig.5.

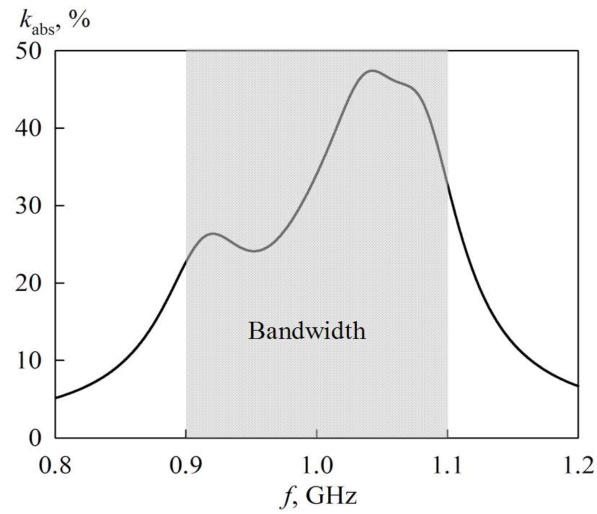


Fig. 5. The frequency dependence of absorption coefficient calculated in the narrow band for the filter with the topology of conductors presented in Fig.3a.

The power absorption maximum frequencies off to the bandpass center are in the good coincidence with the circulating wave resonances calculated frequencies: the first one is when electromagnetic waves are propagate from resonator to resonator clockwise in the structure, the second one – vice versa, counterclockwise.

The structure configuration changing by resonators replacing in the second rank (Fig.3b) allows to avoid the waves such circulation in the structure. In this, the best electromagnetic crystal building version, be observed primary the inductive interaction not only between counter-directional resonators of adjacent ranks, but also between contiguous co-directional resonators in the second rank. This results in cardinal changing of the electromagnetic waves propagation in this 2D microstrip construction. Taking into account the fact that the inductive interaction of the reviewing resonators is much stronger than of the capacitive one, the signal from the ingoing resonator is transmitted to the first resonator of the second rank, then to the second resonator of the same rank and to the outgoing resonator afterwards. In this case in AFCs (Fig.4, solid line) near the bandpass low-frequency and high-frequency slopes the attenuation poles are observed, that is significantly enlarges these slopes steepness. In the bandpass center the microwave power uniform passing is observed with the minimal losses -1.13 dB. The width of the high-frequency stop band is $3f_0$, measured by the -30 dB level.

To deem the developed bandpass filter perspective, it is necessary to compare objectively its parameters with the parameters of other known microstrip filters, for example, filter of the 4-th order [2,4], implemented on one-dimensionally disposed resonators (Fig.3c). Both filters have the stop bands, approximately equal in width (Fig.4, lines). However, the stated filter is much more diminutive: the area of resonators is 346.9 mm^2 versus 560.8 mm^2 of the known one [2,4]. The observed in AFCs attenuation poles enlarge the steepness not only of the high-frequency, but also of the low-frequency bandpass slope. In such a case, the minimal power losses in BP of both filters are equal. However, the existence of the additional capacitive interaction between incoming and outgoing resonators results in power passing increment in the high-frequency stop band.

The geometrical size of strip conductors portions and gaps between them are actual for analyzed filter of the 4-th order are given in the Tab. II.

TABLE II
THE FILTERS STRIP CONDUCTORS PORTIONS SIZES

Filter	Portion position in Fig.	Conductor portion sizes, mm	Earthed
1	2	3	4
Fig.3a	*1*	9.60 × 0.25	–
	2	0.40 × 0.30	–
	3	8.70 × 7.60	–
	4	0.90 × 0.40	–
	5	0.30 × 0.25	Earthed (all area through a substrate on base)
	6	7.90 × 0.30	–
	7	0.30 × 0.30	Earthed (all area through a substrate on base)
	8	7.85 × 0.30	–
	9	0.90 × 0.55	–
	10	9.50 × 0.30	–
	11	8.60 × 7.60	–
	12	0.50 × 0.25	–
	Note. The gaps between adjacent resonators of the same rank are 0.15 mm, between ranks ones are 0.50 mm		

TABLE II CONTINUATION

1	2	3	4
Fig.3b	*1*	8.80 × 0.30	–
	2	0.70 × 0.30	–
	3	8.20 × 8.10	–
	4	0.60 × 0.25	–
	5	0.30 × 0.30	Earthed (all area through a substrate on base)
	6	0.40 × 0.30	–
	7	8.40 × 8.10	–
	Note. The gaps between adjacent resonators of the same rank are 0.45 mm, between ranks ones are 0.40 mm		
Fig.3c	*1*	18.60 × 0.35	Earthed
	2	8.00 × 6.70	–
	3	8.40 × 6.45	–
	Note. The gaps between the first and second resonators are 0.30 mm, between second and third ones are 0.45 mm		

In the whole, we can conclude the perspectiveness of the 2D electromagnetic crystal of 2×2 size for the bandpass filters of high frequency-selective properties implementation on its basis.

Not without clear interest is the enlargement of 2D electromagnetic crystal size with optimal microstrip resonators disposition, as in this case, the bandpass filters of higher order, for instance, of 6-th, can be implemented on its base, thus improving its selective properties.

The topology of the strip conductors of such filter of the 6-th order on the crystal sized 3×2 basis is represented on Pic.6a. The electromagnetic waves propagation in such microstrip structure is equal to the propagation in 2×2 sized crystal. From the incoming resonator to the first resonator of the second rank, then to the second resonator of the same rank, to the second resonator of the first rank, to the third resonator of the first rank and, finally, to the outgoing resonator.

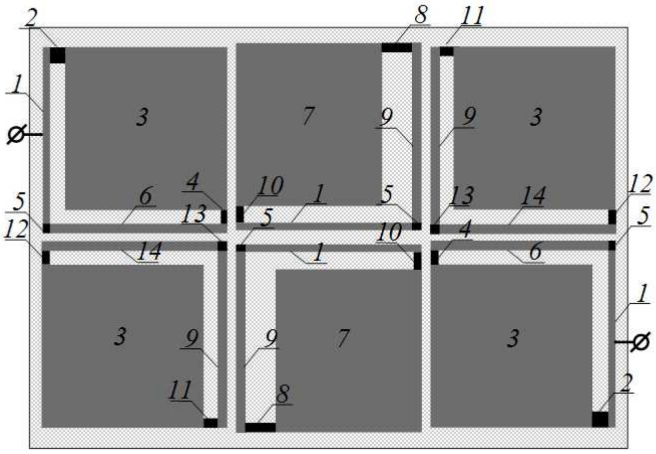
We should notice that the adjustment of BP such construction with needed return losses level at its frequencies is expecting some central resonators separation one from another, as also the proportioning of their geometrical size, somewhat different from contiguous resonators size.

Let us consider the changings observed at the filter's amplitude-frequency characteristic (Fig.8, dashed lines): as expected, the microwave power suppression at stop bands frequencies has increased, and minimal losses while bandpass frequencies passing has increased to 1.54 dB. In this case, four attenuation poles are observed with two of them are disposed too close to the bandpass, right and left from it.

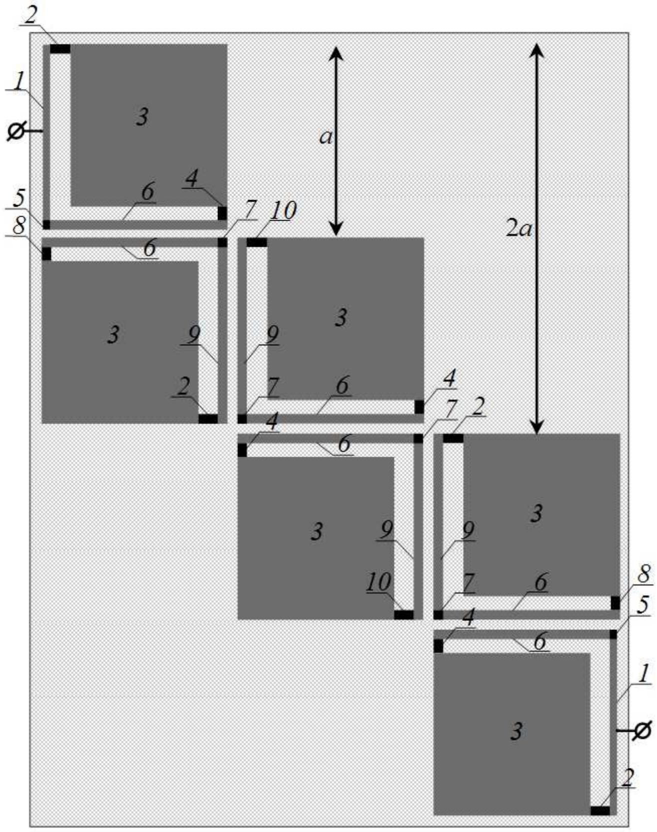
The implementation of the primary inductive interaction between all resonators in the filter of the 6-th order is possible, using the vertical ranks displacement by some quantity, for example, for the lattice period a (Fig.6b).

In this instance, the structure diminutiveness decrease and minimal losses in the bandpass (-2.19 dB) increment are attended by the strong growth of its both two slopes steepness, as also significant power suppression in the stop bands enlargement (Fig.8, solid line). We should notice that at the low-frequency stop band frequencies the passed power is weakened to the level not worse than 104 dB. The high-frequency stop band width is $3.3f_0$, measured by -30 dB level.

For the off-standard ingoing and outgoing 50 Ω ports disposition cases, from the one side of the dielectric substrate, that is sometimes necessary while constructing modern radio devices components, can be used the bandpass filter of the 6-th order based on 2D electromagnetic crystal of 2×4 size with a defect of two absent outermost resonators (Fig.7).



a



b

Fig. 6. Topology of the 6[th] order filters conductors, based on electromagnetic crystal. a – with size 3×2, b – with vertical displacement of resonators ranks.

On the whole, such filter has the similar form of amplitude-frequency characteristic (Fig.8, points) as compared with reviewed multi-chained constructions AFCs, however, near the both bandpass slopes two attenuation poles are observed, that consequently enhances its selective properties. In such a case the minimal losses in the bandpass are not higher than -1.85 dB.

Thus, all reviewed microstrip filters of 6th order on the basis of 2D electromagnetic crystals have high frequency-selective properties: bandpass steep slopes, extensive high-frequency stop band and strong power suppression at the low-frequency stop band frequencies.

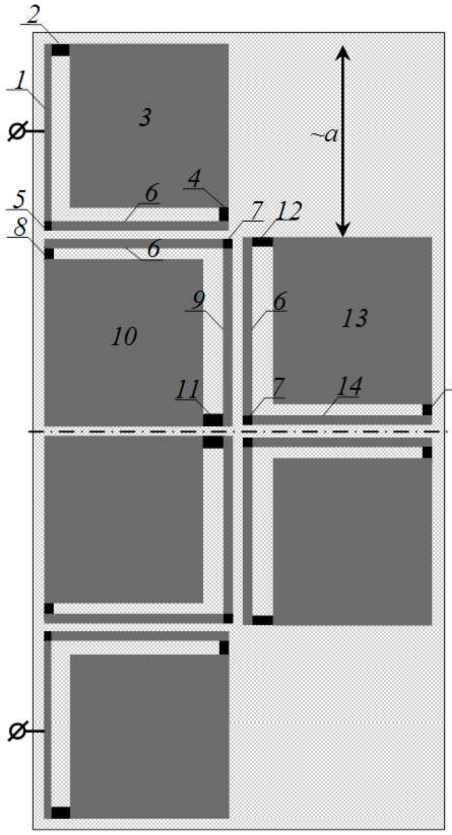


Рис. 7. Topology of the 6[th] order filter conductors, based on electromagnetic crystal with a defect.

The geometrical size of strip conductors portions and gaps between them are actual for analyzed filter of the 6-th order are given in the Tab. III.

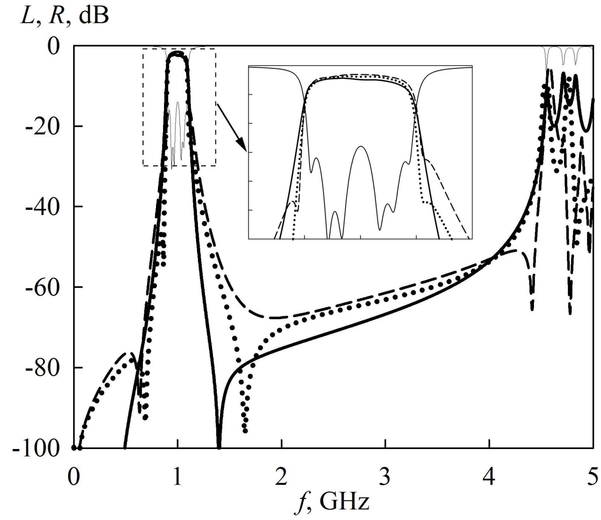


Рис. 8. Synthesized AFCs of 6[th] orders filters. Dashed lines – used the topology of conductors presented in Fig.6a, solid lines– in Fig.6b, points – in Fig.7.

TABLE III

THE FILTERS STRIP CONDUCTORS PORTIONS SIZES

Filter	Portion position in Fig.	Conductor portion sizes, mm	Earthed
1	2	3	4
Fig.6a	*1*	8.70 × 0.25	–
	2	0.65 × 0.55	–
	3	8.20 × 8.20	–
	4	0.50 × 0.15	–
	5	0.30 × 0.25	Earthed (all area through a substrate on base)

TABLE III CONTINUATION

1	2	3	4
Fig.6a	*6*	8.85 × 0.30	–
	7	8.15 × 7.60	–
	8	1.10 × 0.25	–
	9	8.70 × 0.30	–
	10	0.55 × 0.35	–
	11	0.60 × 0.20	–
	12	0.50 × 0.20	–
	13	0.30 × 0.30	Earthed (all area through a substrate on base)
	14	8.80 × 0.30	–
	Note. The gaps between the first and second resonators of the first (second) rank are 0.35 mm; between the second and third resonators of the first (second) rank ones are 0.40 mm; between outermost resonators of the first and second rank ones are 0.35 mm; between central ones are 0.65 mm.		
Fig.6b	*1*	8.70 × 0.20	–
	2	0.70 × 0.30	–
	3	8.30 × 8.15	–
	4	0.40 × 0.35	
	5	0.30 × 0.20	Earthed (all area through a substrate on base)
	6	8.85 × 0.30	–
	7	0.30 × 0.30	Earthed (all area through a substrate on base)
	8	0.40 × 0.30	–
	9	8.70 × 0.30	–
	10	0.70 × 0.35	–
	Note. The gaps between resonators in the direction from ingoing resonator to outgoing one: 0.35 mm, 0.55 mm, 0.55 mm (central), 0.55 mm, 0,35 mm.		
Fig.7	*1*	8.80 × 0.25	–
	2	0.70 × 0.40	–
	3	8.20 × 8.10	–
	4	0.60 × 0.25	–
	5	0.30 × 0.25	Earthed (all area through a substrate on base)
	6	8.80 × 0.30	–
	7	0.30 × 0.30	Earthed (all area through a substrate on base)
	8	0.40 × 0.30	–
	9	8.75 × 0.30	–
	10	8.35 × 8.00	–
	11	0.80 × 0.45	–
	12	0.75 × 0.35	–
	13	8.40 × 8.10	–
	14	8.85 × 0.30	–
	Note. The gaps between ingoing and adjacent resonator are 0.35 mm; between the first and second resonators of the second rank ones are 0.60 mm; between the first resonators of the second and third ranks ones are 0.35 mm; between the second resonators of the second and third ranks ones are 0.40 mm.		

IV. Experimental Results

For verifying the serviceability of the developed constructions and estimating the accuracy of the electrodynamic calculation of their characteristics, we fabricated experimental sample of microstrip filter of the fourth order. In this case, it was «polikor» of 1 mm thick with the permittivity ε = 9.8 that was used as a substrate material. Preliminarily, the topology of the conductors of 2D structure (Fig.9) was obtained by the parametrical synthesis using 3D models. We will note, weakening of a capacitive coupling between resonators of the first rank allows to regulate in addition the steepness of a high-frequency slope of bandwidth and the level of suppression of power at the high-frequency stop band frequencies. The photograph of the filter, having relative width BP $\Delta f/f_0 = 16\%$, and its AFCs are shown in Fig.10. The lines show the results of calculation, and the points show the results of measurements.

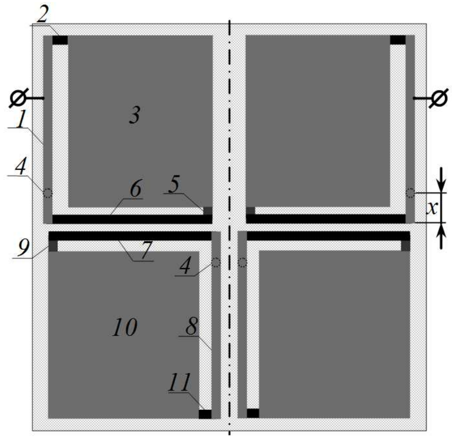


Fig. 9. Topology of the strip conductors of experimental filter.

From Fig.10, it can be seen that the investigated constructions show a reasonably good agreement of the calculated AFCs of filter with the measured ones. The filter have widened high-frequency stop band and admissible losses of the power in the passband ~ 1.5 dB.

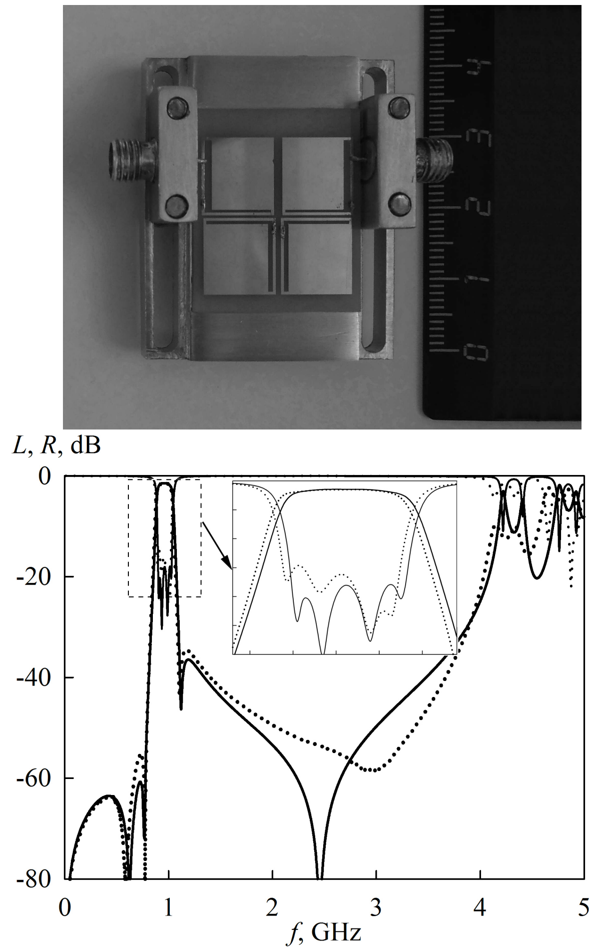


Fig. 10. AFCs of 4th order bandpass filter. Lines are the calculation, and points are the measurements. In the insets we show the photograph of fabricated sample.

It is of importance to note that, for an objective comparison between the results of experiment and calculation, we substituted the real sizes of topology of the conductors measured by microscope in already made filter by engraving method on a varnish (Fig.9), for the 3D model. These average sizes are listed in the Tab. IV.

TABLE IV
THE EXPERIMENTAL FILTER STRIP CONDUCTORS PORTIONS SIZES

Filter	Portion position in Fig.	Conductor portion sizes, mm	Earthed
Fig.9, Fig.10, the photograph	*1*	10.10 × 0.35	–
	2	0.95 × 0.35	–
	3	9.40 × 8.05	–
	4, it is displaced on x =1.3 mm from edge of portion of the conductor *1 (8)*	0.40 (diameter)	Earthed (all area through a substrate on base)
	5	0.35 × 0.35	–
	6	9.00 × 0.35	–
	7	9.05 × 0.35	–
	8	9.90 × 0.35	–
	9	0.45 × 0.35	–
	10	9.10 × 8.40	–
	11	0.65 × 0.35	–
	Note. The gaps between adjacent resonators of first rank are 1.13 mm, between ranks ones are 0.36 mm.		

V. DISCUSSION OF RESULTS

Thus, the research results have shown that diminutive irregular microstrip resonator with rolled up strip conductors portions that have a common earthing on the basis is perspective while building filters of the wide stop band on the basis of 2D electromagnetic crystals.

In this case, while changing the disposition of such co-directional or counter-dimensional resonators in the space the different electromagnetic coupling between them can be implemented, both primary inductive one and primary capacitive one. Thereby the circulating wave resonances can be avoided in the 2D microstrip structures, the sequential one to another resonator signal transmission is needed. This allows to construct bandpass filters of high frequency-selective properties.

Thus, the filter of 4th order on the 2×2 size crystal basis must have primary inductive interaction not only between counter-dimensional resonators of the adjacent ranks, but also between contiguous co-dimensional resonators of the second rank. Then at the AFCs near both bandpass slopes the attenuation poles are observed that significantly raises their steepness, while the high-frequency stop band width, measured by -30 dB level, reaches value not less than $3f_0$.

The raise of resonators number in the structure is attended by expansion in the number of filters construction with high electrical characteristics: bandpass steep slopes, extensive high-frequency stop band and strong power suppression at both low-frequency and high-frequency stop band frequencies. All this can be observed at AFCs of the represented in the work bandpass filters of the 6th order. In such instance, every one of them has its individual specialties: the filter based on the 3×2 sized crystal is distinct in compact resonators disposition, and, consequently, in diminutiveness, the vertical ranks displacement in it for the lattice period allows to implement the power suppression in the low-frequency stop band more than 100 dB. In the AFCs of the filter on the basis of 2×4 sized crystal that has a defect of two absent outermost resonators two attenuation poles can be observed near each bandpass slope.

We should notice that the perspectiveness of the developed constructions is due to their not only electrical characteristics, which can be enhanced by enlarging electromagnetic crystal size, but also to the technological efficiency and good coincidence of the 3D filters models electrodynamic analysis with the experiment.

VI. CONCLUSION

There were introduced the brand new constructions of the bandpass filters on the basis of the electromagnetic crystal of the 2D disposition of the microstrip resonators with the rolled up strip conductors portions that have common earthing on the base.

In such a case it is necessary to select their spatial configuration so that the electromagnetic waves propagation proceeds consequently from one resonator to another. This allows to construct different orders filters of high frequency-selective properties: widened high-frequency stop band $3.3f_0$, measured by the -30 dB level, the power suppression in the low-frequency stop band more than 100 dB and bandpass steep slopes.

The comparison of experimental measurements received on the fourth order filter with passband width $\Delta f/f_0 \approx 16\%$ with the results modeled by the electrodynamic numerical analysis of 3D models shows the good consent.

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