# Investigation of Irregular Microstrip Resonators and Wideband Filters Based on Them

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*Abstract* – **New multimode irregular microstrip resonators and designs of wideband bandpass filters based on them are being theoretically and experimentally investigated. A central multimode resonator electromagnetically connected with single-mode or two-mode resonators at the input and output of a structure are used in the developed filters. It is the first experience giving the possibility of combining inherent frequencies up to six lowest modes of oscillations, which are involved in the formation of the bandpass of the multimode resonator. Strong interaction of oscillations modes leads to its significant extension.**

*Index Terms* – **Bandpass filter, multimode resonator.**

## I. INTRODUCTION

WHILE developing new structures of frequency-selective microwave (MW) devices, e.g., bandpass filters, developers traditionally try to expand their selective properties, to improve processability index, to reduce the dimensions and to reduce the cost of the finished products as well. Various microstrip structures meet all of the above mentioned requirements, making them widely used in microwave equipment [1,2].

It is known [3] that rectangular strip conductor set on a dielectric substrate is the simplest single-mode microstrip resonator. Its amplitude–frequency characteristic (AFC) is rather accuratly calculated even with a quasi-static approximation. In this connection, if a strip conductor of a resonator is split, multimode operating conditions are being realized when several modes of oscillations form operating bandpass of a device. Filters based on these resonators will have improved frequency-selective properties, however, in order to conduct such prospective studies it is necessary to use numerical electrodynamic analyses of their 3D models, that obviously requires computers of high capacity.

Among known microstrip resonators miniature two-mode resonators with regular rectangular strip conductor partially digested at one end by a narrow slot are of greatest interest [4-6]. However, in this case the connection of first two resonator oscillation modes is small, and is shown in a slight difference in length of conductors on their split area. This circumstance does not allow to create a broadband filters on such resonators, however filters with narrow bandwidth have rather high frequency-selective properties even in structures consisting of only two or three resonators [7-9].

Therefore, this paper gives the results of studies of microstrip resonators operating in multimode conditions, arising due to the slots and cutouts in strip conductor. Moreover, the article represents new structures of broadband filters being based on them.

## II. PROBLEM DEFINITION

In the present article it is proposed to research the multimode resonators and designs of bandpass filters based on them.

For achieving this purpose the following problems must be sold:

- 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;
-topology developing of strip conductors of multimode resonators with number of the modes forming bandwidth not less than five;
- examination of frequency-selective properties of various microstrip bandpass up to the tenth-order filters on the basis of such resonators;
- appreciate the accuracy of the electrodynamic numerical analysis of the microstrip structure 3D model, comparing the calculated characteristics of the filter of the wide bandwidth with the measured on the experimental sample ones.

## III. THEORY

In order to have certainty and ability of objective comparison of frequency-selective properties, the investigated resonators and filter structures based on them were tuned to the same central frequency of bandwidth $f_0$=1.25 GHz by selecting the geometric dimensions of strip conductors and cutouts in them. In this case mainly the substrate of TBNS ceramics (material that is widely used in MW devices) with thickness $h$ = 1 mm having high dielectric permittivity $\varepsilon = 80$ were used as the bedding of microstrip structures. Parametric synthesis of all the constructions was carried out with the help of numerical electrodynamic analysis of 3D models in which the input and output ports had wave resistance of 50 Ω and were conductively connected to the connection conductors.

As it is well known [4,5,7-9], a rectangular slot in the strip conductor of a single-mode resonator allows to bring two low-frequency oscillation modes together, one of which is even, and the other is odd. For the convergence of a larger number of oscillation modes in such resonator it is necessary to use several slots and cutouts in its strip conductor.

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Thus, for the implementation of a bandwidth formed by five resonances (Fig.1, solid lines) it is necessary to make in the strip conductor *1* (the original rectangular outline of which is shown by dash lines in Fig.2*a*), one slot *2* in its upper part, next to the dots of conductive connection to the microwave path and two symmetrical (one to another) cutouts *3* - in its lower part. As a result, the conductor gets shape similar to the letter «*Y*».

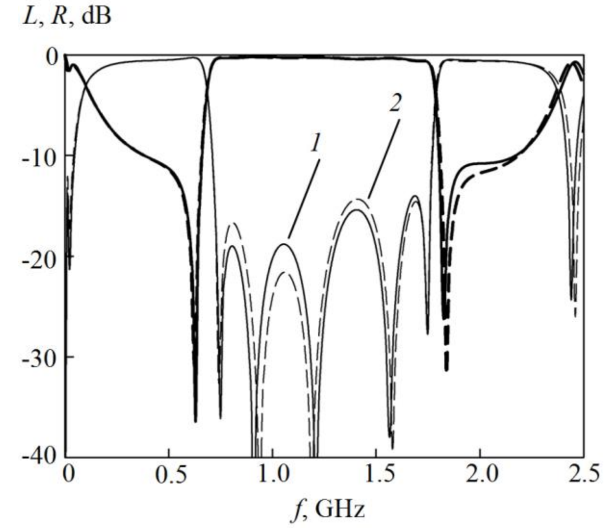


Fig. 1. AFCs of the five-mode resonator with strip conductor of *Y*-shape (*1*) and of *Ш*-shape (*2*).

In this case, the three resonances getting to the frequency of a bandwidth are caused by high-frequency currents going through the segments of strip conductors along the contour of the extended recess *2*. Two lowest modes of resonator's oscillation forming bandwidth are caused by the currents flowing through the zigzag vertical conductors. Due to specific topology of the conductor extended along the two axes and the irregularities in it, all five resonances are non-degenerate, and they form bandwidth band.

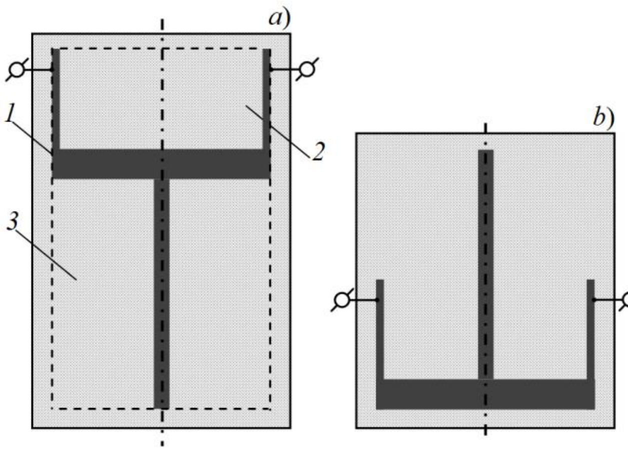


Fig. 2. Topology of the strip conductor (black or gray) of five-mode resonators.

A significant miniaturization of the considered resonator is achieved by placing the lower vertical segment of the strip conductor within the slot, as shown in Fig.2*b*, in this case a strip conductor similar to the Russian letter «*Ш*». At the same time, as one would expect, the resonator has approximately identical amplitude-frequency characteristics (Fig.1, dash line), while maintaining the geometric dimensions of all the segments of strip conductors.

Splitting the original strip conductor by two adjacent rectangular slots *2* and *3*, as shown in Fig.3, allows to realize bandwidth formed by six resonances (Fig.4). For low-frequency oscillation modes on the adjacent strip segments separated by slots, high frequency currents can go either in one direction or in opposite directions, but meanwhile there are no currents at unsplit strip segment.

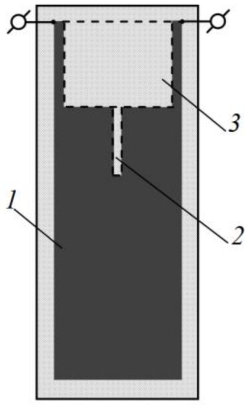


Fig. 3. Topology of the strip conductor of six-mode resonator. The outline of rectangular slots *2* and *3* on the conductor is shown by dash lines.

Due to the extended slot *3* in the strip conductor *1* and a narrow slot *2*, it is possible to bring the frequency of four lowest modes of oscillations of a multimode resonator together for them to be involved in the formation of the bandwidth.

It is necessary to note that in considered resonators on the amplitude-frequency characteristics to the left and to the right from bandwidth one observes poles of power attenuation.

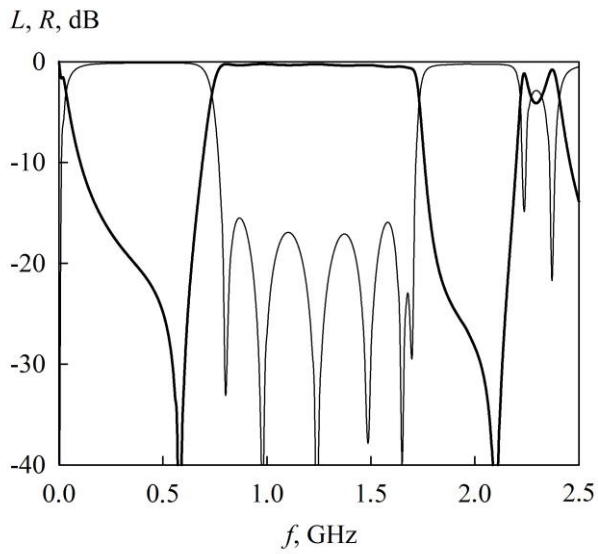


Рис. 4. AFCs of the six-mode resonator.

The geometrical size of strip conductors segments of the investigated resonators are given in the Tab. I.

TABLE I
THE RESONATORS STRIP CONDUCTORS SEGMENTS GEOMETRICAL SIZES

| Resonator | Segment position in Fig. | Conductor sizes, mm² | Slots sizes, mm² |
|---|---|---|---|
| Fig.2*a* | *1* | 25.70 × 15.60 | |
| | *2* | | 15.00 × 7.20 |
| | *3* | | 16.35 × 7.20 |
| Fig.3 | *1* | 28.00×9.90 | |
| | *2* | | 5.70×0.30 |
| | *3* | | 6.60×8.70 |

Such miniature multimode resonators are mainly of great interest for developers of modern high-tech radio navigation and communication systems, including space devices. Broadband microstrip bandpass filters with high frequency-selective properties can be realized by adding single-mode or two-mode extreme resonators to the structure. In this case multimode resonators become central ones (Fig.5 and Fig.7).

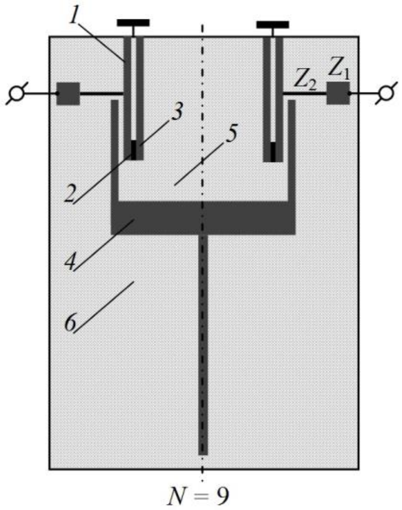


Fig. 5. Topology of the strip conductors of 9th order filter based on five-mode resonator.

Let us consider the structure of broadband filter based on five-mode resonator in details (Fig.5). The conductors *1-3* of extreme two-mode resonators are connected to the grounding from the free ends and are situated inside a rectangular cutout *5* of strip conductor *4*. This allows to use free of metallization area more effective and thereby to miniaturize the filter structure having a relative wide bandwidth $\Delta f/f_0 = 95\%$ and losses in it $L_{min} \approx 0.82$ dB. Strong interaction of all nine oscillation modes involved in the formation of bandwidth is the reason of significant expansion of one (Fig.6).

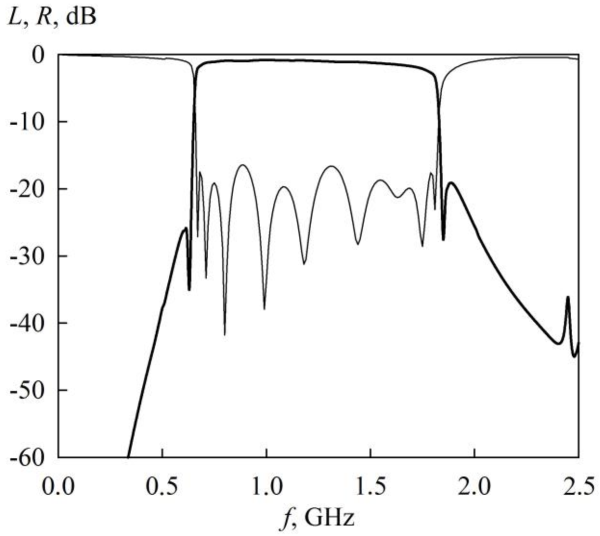


Fig. 6. AFCs of 9th order filter based on five-mode resonator.

It is important to note that there are poles of power attenuation at AFC device next to low and high frequency slopes of wide bandwidth, that leads to symmetrical increase of these slopes. While 3D modeling, for added tuning of return loss level in the bandwidth a discontinuity of lines resistance $Z_1/Z_2 = 0.35$ was used. It is realized by introduction into the structure (perpendicular to the conductor segments *1* from each side) the two small sequentially connected segments of strip conductors with wave resistance $Z_1$ and $Z_2$, respectively (Fig.5). In this case the first segment of this kind becomes a filter port. This makes the coordination of the structure with the MW path easier.

It should be noted that in such bandpass filter, the expansion of bandwidth is followed by contraction of high frequency stopband and by the appearance of idle bandwidths at the frequencies corresponding to the ones of the highest modes of a multimode resonator oscillation. Therefore, further increase of resonator available modes number at such arrangement of electromagnetic connections and use of grounded conductors of two-mode resonators does not lead to the improvement of the selective properties of wideband filters.

At the same time, it is possible to realize more challenging and technological broadband bandpass filter based on the considered resonator (see. Fig.3). Unfolded to 180° extreme resonators with strip conductors *1-3* not grounded at the base were used in the microstrip structure (Fig.7a) in order to do that. In this case, one can organize both single-mode and more complicated in realization – two-mode operating conditions of such resonators.

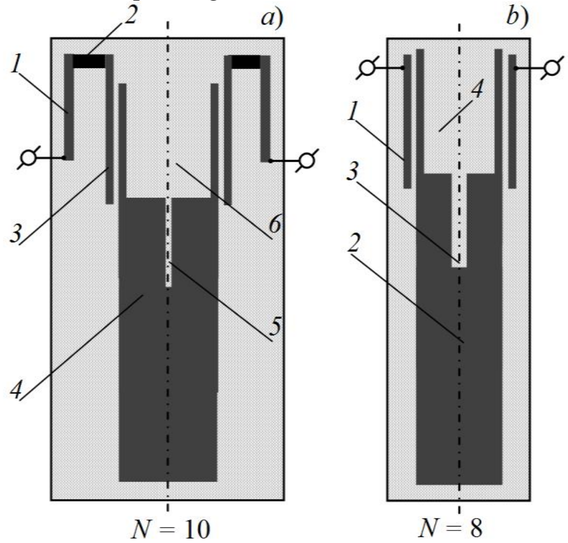


Fig. 7. Topology of the strip conductors of 9th (*a*) and 10th (*b*) orders filters based on six-mode resonator.

Bandwidth filter with relative width $\Delta f/f_0 \approx 86\%$, measured at level of -3 dB from the minimum loss level $L_{min} = 0.67$ dB is formed by ten resonances. One should note that the last but one high frequency spike of the inverse loss in bandwidth contains two resonance at the depicted amplitude-frequency characteristic (Fig.8, lines). The existence of attenuation poles situated to the left and to the right of the bandwidth gives extra selective construction possibilities.

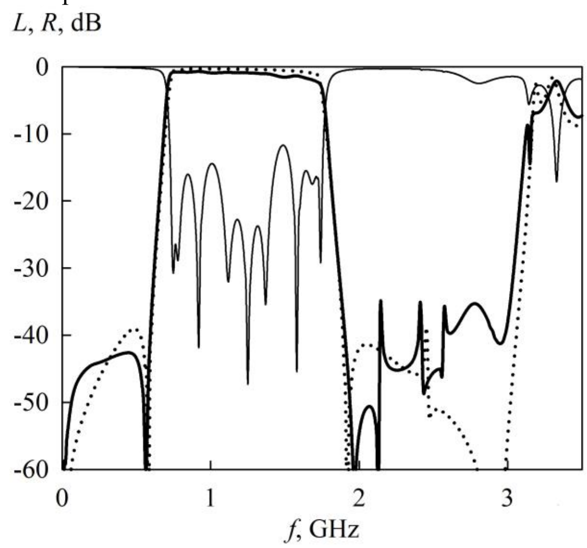


Fig. 8. AFCs of 10th (lines) and 8th (points) orders filters.

It is crucial to mention that such wideband filter can be implemented not only on the substrate with high dielectric permittivity (ε = 80), but with low as well, e.g., ceramics «B20» (ε = 20) and «polykor» (ε = 9.8). The extreme half-wave two-mode resonators of *П*-shape are replaced by quarter-wave single-mode ones (Fig.7*b*) that are narrow regular strip conductors *1*. The amplitude-frequency characteristics of the turned filters are slightly different for all three substrates, therefore, in Fig.8, additional points show synthesized AFC of the filter, implemented on polikor substrate.

The size of strip conductors of the discussed three broadband microstrip bandpass filters are given in the Tab. II.

TABLE II
THE FILTERS STRIP CONDUCTORS SEGMENTS SIZES

| Filter and (ε) of substrate | Segment position in Fig. | Conductor sizes, mm² | Slots sizes, mm² | Displacement from the substrate edge, mm |
|---|---|---|---|---|
| Fig.5 (80) | *1* | 11.00 × 0.06 | | 0 (earthed) |
| | *2* | 1.68 × 0.21 | | 9.32 |
| | *3* | 11.00 × 0.08 | | 0 (earthed) |
| | *4* | 27.50 × 14.86 | | 5.90 |
| | *5* | | 14.54 × 8.20 | |
| | *6* | | 16.40 × 6.96 | |
| | Note. The gap between the segments of conductors *1* and *3* is 0.21 mm, between the segment of conductor *1* and conductor *4* is 0.05 mm | | | |
| Fig.7*a* (80) | *1* | 7.90 × 0.20 | | 1.00 |
| | *2* | 3.55 × 0.70 | | 1.00 |
| | *3* | 11.60 × 0.15 | | 1.00 |
| | *4* | 30.00 × 7.55 | | 3.20 |
| | *5* | | 7.20 × 0.05 | |
| | *6* | | 8.60 × 7.35 | |
| | Note. The gap between the segments of conductors *3* and conductor *4* is 0.10 mm | | | |
| Fig.7*b* (9.8) | *1* | 25.10 × 0.20 | | 2.80 |
| | *2* | 85.2 × 11.40 | | 1.00 |
| | *3* | | 20.50 × 0.40 | |
| | *4* | | 23.80 × 11.00 | |
| | Note. The gap between the conductors *1* and *2* is 0.10 mm | | | |

## IV. EXPERIMENTAL RESULTS

For verifying the serviceability of the developed selective structures and estimating the accuracy of the electrodynamic calculation of their electrical characteristics, we fabricated experimental sample of microstrip filter based on the six-mode resonator. In this case, it was «TBNS» of 1 mm thick with the permittivity ε = 80 that was used as a substrate material. The topology of the strip conductors of wideband filter (Fig.7*a*) was obtained by the parametrical synthesis using 3D models. Its AFCs are shown in Fig.9. The lines show the results of calculation, and the points show the results of measurements.

Experimental model of a design (Fig.9, photograph) show a reasonably good agreement of the calculated AFCs of filter with the measured ones.

Bandwidth of wideband filter is formed by eight resonances: six ones are from the multimode central resonator and two ones are from extreme resonators. At the same time the high steepness of bandwidth slopes is also caused by the poles of attenuation of power located near. We will note that the filter bandwidth is $\Delta f/f_0 \approx 85\%$, measured at level of -3 dB from the minimum loss level $L_{min} = 0.71$ dB.

Measured by microscope the data of microstrip design, made by a photolithography method were: length and width of conductor segment *1*, *2*, *3*: 7.897×0.198 mm², 3.551×0.701 mm² и 11.597×0.148 mm², respectively.

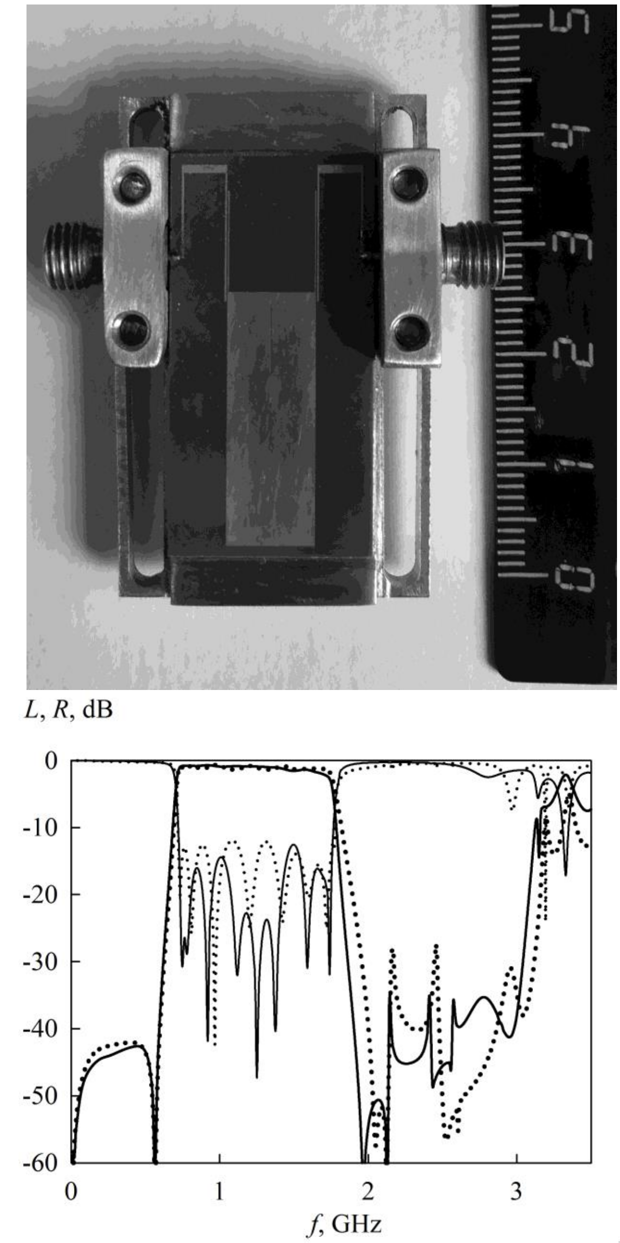


Fig. 9. AFCs of wideband filter. Lines are the calculation, and points are the measurements. In the insets we show the photograph of fabricated sample.

The area of a narrow slot *5* is 7.203×0.049 mm², one of a wide slot *6* is 8.600×7.349 mm². They are situated inside a rectangular conductor *4:* 30.03×7.552 mm². The gaps between extreme resonators and central one are 0.098 mm. Displacement from the top of substrate edge the conductor segment *2* is 0.994 mm, and similar displacement of the resonator *4* is 3.194 mm.

## V. DISCUSSION OF RESULTS

The present paper represents the results of studies of two new of miniature microstrip resonators with slots and cutouts in strip conductors. In the first one, strip conductor has shape similar to the letter «*Y*». This helps to bring together frequencies of its five lowest oscillation modes being involved in the process of bandwidth formation.

A considerable miniaturization of this resonator is achieved by placing the lower segment of the strip conductor inside the cutout, as a result the strip conductor gets similar to the Russian letter «*Ш*», but meanwhile the amplitude-frequency characteristics stay practically unchanged.

In a second microstrip resonator the strip conductor is split by two adjacent rectangular slots, while its bandwidth is formed by six resonances.

While constructing these microstrip wideband filters, the resonators were used as central ones, electromagnetically connected with single-mode or two-mode irregular resonators at the input and output of selective structures. Such approach allows to realize bandpass filters of $8^{th}$-$10^{th}$ orders with relative width of bandwidth up to $\Delta f/f_0 \approx 95\%$. It is not difficult to improve the frequency-selective properties of the proposed construction based on six-mode resonator by increasing the number of single-mode or two-mode resonators.

It is necessary to note that in all investigated structures based on a multimode resonator one can observe poles of power attenuation in amplitude-frequency characteristics almost symmetrically to the left and to the right from the bandwidth that essentially increases of bandwidth slopes. The value of minimum loss in the bandwidth is less than 1 dB.

We should notice that the perspectiveness of the developed frequency-selective constructions is due to their not only electrical characteristics, but also to the technological efficiency and good coincidence of the 3D filters models electrodynamic analysis with the experiment.

## VI. Conclusion

Hereby, new multimode microstrip resonators with slots and cutouts in the strip conductors and the structure of broadband bandpass filters on their base up to tenth order are proposed and investigated.

It was the first experience to use slots and cutouts in the strip conductors that allows combining the multimode resonator up to six lowest oscillation modes, which are involved in the formation of the bandwidth. The significant expansion of bandwidth is achieved by strong interaction of all oscillation modes.

One can realize wideband bandpass filters with high frequency-selective properties by increasing their order *N* on the basis of the proposed six-mode resonator.

Electrical characteristics measurements of the experimental model of microstrip bandpass filter with a relative width of bandwidth $\Delta f/f_0 \approx 85\%$, showed good coincidence with the results of numerical electrodynamic analysis of the device using 3D models.

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