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PHYSICS

Investigation of Microstrip Structures of Wideband Bandpass Filters

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When designing new constructions of frequency-selective microwave devices, in particular, filters, engineers traditionally try to increase their selectivity, improve the technological efficiency, and decrease the dimensions and the cost price. All these requirements are fulfilled by various microstrip constructions; for this reason, they find a reasonably wide application in the microwave technique [1, 2]. However, it is especially necessary to single out the constructions of bandpass filters on two-mode resonators. In the formation of the passband of such devices, the resonances of two oscillation modes from each resonator are involved instead of only one mode as in typical microstrip filters. As a result, the order of the filter, which depends, as is known, on its selectivity, increases twice. It is of importance to note that the passband losses essentially decrease simultaneously with the dimensions in comparison with traditional constructions due to the small number of chains in such filters. The filters on three-mode resonators also have the above advantages [3].

The strip conductors of two-mode resonators in the microstrip filter usually have the shape of a square or a square or rectangular frame, and sometimes they are made like a closed meandering-like line also having the symmetry axis of the fourth order [1, 4]. The eigenfrequencies of the first two oscillation modes of such resonators are degenerate, and the spatial distributions of amplitudes of high-frequency fields are orthogonal. In this case, the necessary value of coupling between the resonances of the two oscillation modes in the bandpass filter is provided either by etching of one of the conductor corners having the shape of a square or a square frame, or by adding a piece of the slot-hole line or a strip element of coupling, which, as a rule, are arranged at an angle of 45° to the resonator axes.

The two-mode resonators, the regular strip conductor of which is partially split from one end with a narrow crack [5], are more miniature. In this case, the value of coupling between the first two oscillation modes of the resonator is low, and it is implemented by a small difference in the length of conductors on its split portion. This circumstance prevents fabricating “wideband” filters on such resonators; however, the filters with a “narrow” passband on them have reasonably high frequency-selective properties even in the constructions consisting of only two or three resonators [6, 7]. The original construction of the wideband microstrip filter on asymmetric two-mode resonators is described in the patent [8], regular investigations of which showed the possibility of implementation of devices with a relative passband width above 50%, but only on the substrates with the permittivity $\varepsilon \geq 10$ [9].

In this work, we investigated the microstrip constructions of filters on new multimode resonators of a certain shape of strip conductors. For the first time, we showed the possibility of rapprochement of eigenfrequencies from the lowest two to six oscillation modes. In this case, the filters on such multimode resonators are implemented also on the substrates with a low permittivity instead of only on those with a high permittivity. We considered the microstrip structures consisting of one multimode resonator having electromagnetic coupling with single-mode half-wave or quarter-wave resonators [10] to which the device ports are connected. Such constructions due to the attenuation poles existing near the passband result in increased steepness of the slopes of the amplitude–frequency characteristics (AFCs), wide stop bands, and a high suppression level of microwave power in them.

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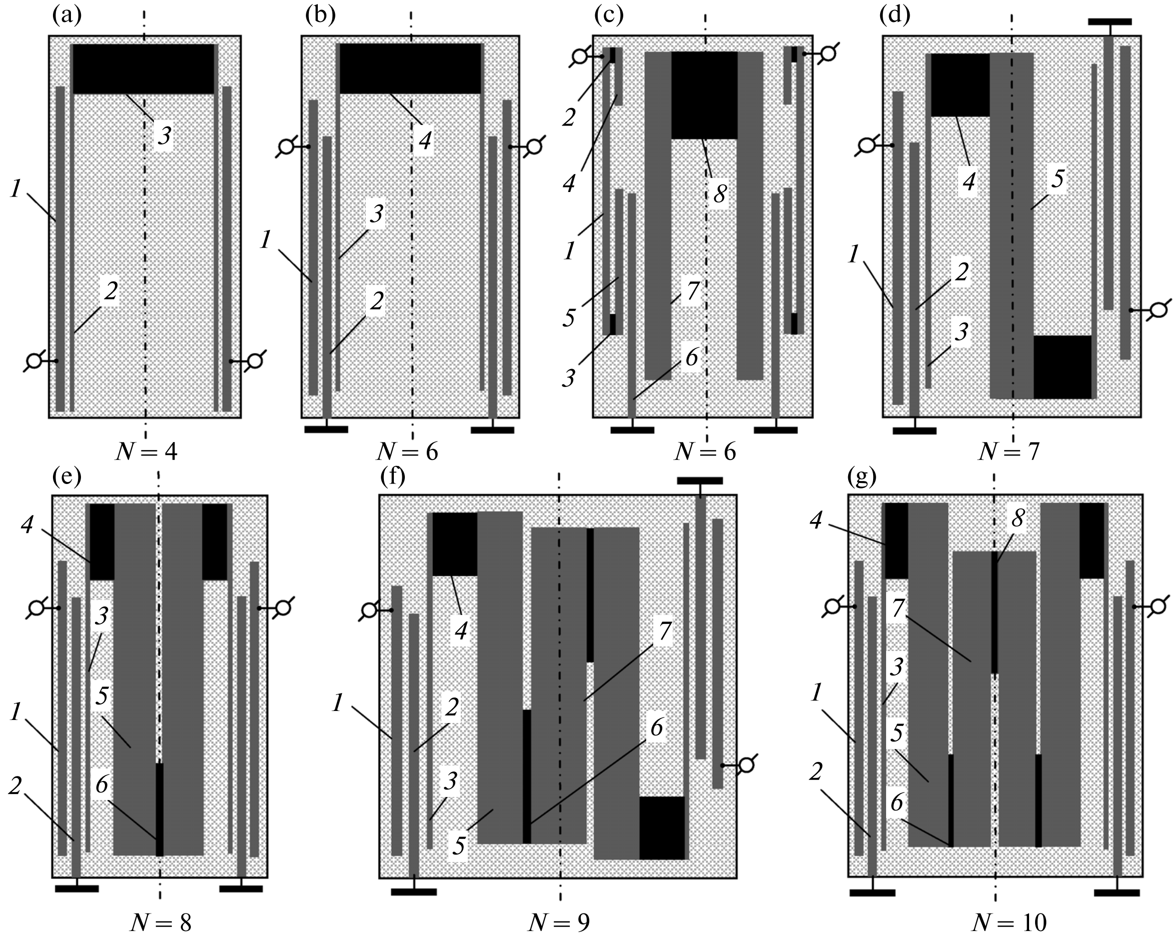

Fig. 1. Topology of conductors of filters of the fourth through tenth orders under investigation. Regular portions of conductors are designated by numbers and shown either in black or in gray.

ANALYSIS OF MICROSTRIP CONSTRUCTIONS OF WIDEBAND BANDPASS FILTERS

For definiteness and objective comparison of frequency-selective properties, the microstrip-filter constructions under investigation (Fig. 1) were adjusted to an identical central passband frequency $f_0 = 1.4$ GHz and an identical relative passband width $\frac{\Delta f}{f_0} = 80\%$ measured at the level of –3 dB from the level of minimal losses. In this case, as substrates of filters, we used plates of thickness $h = 2$ mm from the material FLAN with the permittivity $\varepsilon = 2.8$ widely used in the microwave technique. The parametrical synthesis of filters was carried out with the help of the numerical electrodynamic analysis of 3D models, in which the input and output ports with a wave resistance of 50 Ω are conductively connected to the strip conductors of end resonators. In this case, we selected the geometrical sizes of the topology of conductors including the length and width of regular portions and also the size of gaps between these regular portions.

The first of the constructions under consideration (Fig. 1a) consists of three resonators, two of which are the single-mode quarter-wave ones located at the input and output of the filter and electromagnetically coupled with the two-mode resonator having an irregular strip conductor in the form of a hairpin consisting of two regular portions *2* and *3*. It is of importance to note that the wave resistance of the microstrip lines forming the single-mode resonators of the construction under investigation much exceeds the wave resistance of the ports; therefore, these resonators are quarter-wavelength [4]. We note also that the single-mode hairpin resonators have been investigated reasonably well [11, 12]; however, their interaction is relatively weak, therefore, it is impossible to fabricate wideband filters on them. In the three-resonator filter under consideration, it is possible to draw together the resonant frequencies of its first two oscillation modes due to the broadening of the central portion of the

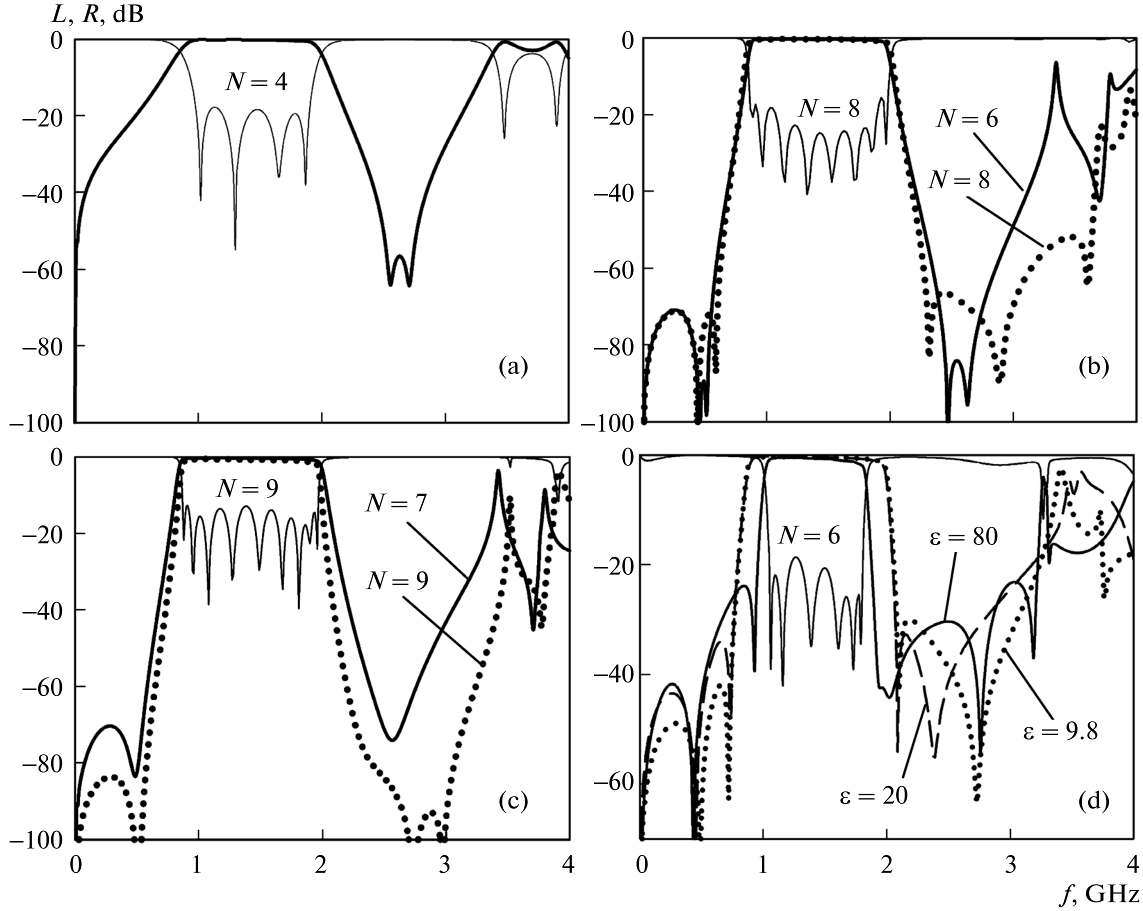

Fig. 2. AFCs of the wideband bandpass filters of the fourth through ninth orders.

conductor of the hairpin resonator shown in Fig. 1a with black (*3*). Therefore, the filter order becomes $N = 4$, which is seen well in its frequency dependence $R(f)$ of losses in reflection (Fig. 2a) shown by the thin line, and the thick line shows the frequency dependence $L(f)$ of direct losses.

The second construction of the filter (Fig. 1b) differs from the first one in having two quarter-wave resonators at the input and output, one end of the strip conductor of each of the additional resonators being connected to the grounding. The third construction (Fig. 1c) is similar to the second one; however, we used the substrate from TBNS ceramics with a high permittivity ($\varepsilon = 80$). On such a substrate, the wave resistance of the microstrip lines forming the single-mode end resonators is lower than that of the ports, and it means that the input and output resonators become half-wave, i.e., their strip-conductor length increases twice. For decreasing the sizes of filters, the strip conductors of these end resonators are rolled in the form of the letter C. It should be noted that this filter was adjusted to a relative passband width $\frac{\Delta f}{f_0} = 60\%$. It is obvious that these constructions of filters have the identical order $N = 6$, and their AFCs are shown in Figs. 2b and 2d.

The remaining constructions of filters differ from those described above in the fact that the two-mode hairpin resonator is replaced for the three-mode (Fig. 1d), four-mode (Fig. 1e), five-mode (Fig. 1f), and six-mode (Fig. 1g) resonators, which correspondingly results in increasing the filter order N from 7 to 10. The strip conductors of all multimode resonators have the shape of an irregular meander. The amplitude-frequency characteristics of constructions of the filters with orders from 4 to 9 are shown in Fig. 2, while the sizes of all regular portions of the topology of the conductors of the filters synthesized on the substrates with $\varepsilon = 2.8$ are given in Table 1. In Table 2, we listed only the sizes of regular portions of the topology of conductors of sixth-order filters fabricated on substrates with various permittivities.

As should be expected, the rectangularity of the filter AFC increases with the filter order; however, we

Table 1. Conductor-topology sizes for the filters of the fourth through ninth orders on substrates with permittivity ε = 2.8

Filter construction	Conductor number	Conductor sizes, mm	Displacement from the substrate edge, mm	Gaps between conductors, mm
Fig. 1a	*1*	41.60 × 0.75	2.00	*1* and *2*—0.21
	2	46.90 × 0.65	2.00	
	3	13.10 × 6.20	40.70	
Fig. 1b	*1*	39.40 × 0.60	3.50	*1* and *2*—0.25, *2* and *3*—0.35
	2	36.40 × 0.70	0 (earthed)	
	3	45.50 × 0.75	3.80	
	4	19.40 × 5.70	43.60	
Fig. 1d	*1*	43.00 × 0.85	2.60	*1* and *2*—0.15, *2* and *3*—0.35
	2	36.70 × 0.80	0 (earthed)	
	3	47.50 × 0.50	2.80	
	4	9.80 × 6.50	40.50	
	5	47.90 × 5.70	2.40	
Fig. 1e	*1*	42.70 × 0.95	2.20	*1* and *2*—0.15, *2* and *3*—0.35
	2	37.20 × 0.70	0 (earthed)	
	3	48.20 × 0.40	3.10	
	4	10.6 × 3.45	40.70	
	5	48.10 × 5.90	3.20	
	6	12.60 × 0.20	3.20	
Fig. 1f	*1*	37.20 × 0.60	4.40	*1* and *2*—0.25, *2* and *3*—0.40
	2	37.00 × 0.55	0 (earthed)	
	3	46.30 × 0.15	6.80	
	4	9.30 × 7.05	43.80	
	5	46.50 × 6.70	6.60	
	6	15.70 × 0.10	6.60	
	7	44.10 × 8.15	6.60	

observed an additional increase in the steepness of AFC slopes and the value of suppression of the microwave power in the stop band due to the presence of the attenuation poles. It should be noted that the electromagnetic waves undergo strong reflection from the filter input due to the mutual compensation of inductive and capacitive interaction between resonators on the frequencies of attenuation poles [13]. An increase in the filter-substrate permittivity results in a corresponding decrease in the device sizes (see Table 2). It is of importance also to note that the considered constructions of filters have the also almost symmetric shape of the AFC instead of only a high steepness of slopes.

RESULTS OF INVESTIGATIONS OF EXPERIMENTAL SAMPLES

For verifying the serviceability of the developed constructions of wideband bandpass filters and estimating the accuracy of the electrodynamic calculation of their characteristics, we fabricated experimental samples of devices of the eighth and tenth orders (see Figs. 1e, 1g). In this case, it was FLAN of 2 mm thick with the permittivity ε = 2.8 that was used as a substrate material. Preliminarily, the topology of the conductors of filters was obtained by the parametrical synthesis using 3D models. The eighth-order filter was adjusted to the relative passband width $\frac{\Delta f}{f_0} = 80\%$, while the tenth-order filter fit with the largest passband width $\frac{\Delta f}{f_0} = 95\%$, which was determined by the accuracy of manufacturing the narrowest gaps between the strip conductors. The photographs of the fabricated constructions and their AFCs are shown in Fig. 3. The lines show the results of calculation, and the points show the results of measurements. It is of

Table 2. Conductor-topology sizes for the filters of the sixth order on substrates with various permittivities ε

Filter construction	Conductor number	Conductor sizes, mm	Displacement from the substrate edge, mm	Gaps between conductors, mm
Fig. 1b (9.8)	*1*	23.80 × 0.20	6.60	*1* and *2*—0.10, *2* and *3*—0.25
	2	19.10 × 0.25	0 (earthed)	
	3	29.00 × 0.80	0.30	
	4	7.40 × 5.70	23.60	
Fig. 1b (20)	*1*	20.60 × 0.15	0.40	*1* and *2*—0.10, *2* and *3*—0.15
	2	13.80 × 0.20	0 (earthed)	
	3	21.20 × 1.15	2.50	
	4	5.10 × 4.30	18.60	
Fig. 1c (80)	*1*	9.50 × 0.15	2.70	*5* and *6*—0.10, *6* and *7*—0.40
	2	0.50 × 0.10	11.70	
	3	0.70 × 0.10	2.70	
	4	1.90 × 0.20	10.30	
	5	4.70 × 0.15	2.70	
	6	7.30 × 0.15	0 (earthed)	
	7	10.80 × 0.80	1.20	
	8	2.90 × 2.2	9.10	

Table 3. Conductor-topology sizes for the filters of the eighth and tenth orders on substrates with permittivity ε = 2.8 of 2 mm thick

Filter construction	Conductor number	Conductor sizes, mm	Displacement from the substrate edge, mm	Gaps between conductors, mm
Fig. 1e	*1*	42.69 × 1.01	2.21	*1* and *2*—0.20, *2* and *3*—0.39
	2	37.20 × 0.71	0 (earthed)	
	3	48.20 × 0.32	3.94	
	4	10.58 × 7.92	41.56	
	5	48.09 × 6.72	4.05	
	6	12.67 × 0.20	4.05	
Fig. 1g	*1*	41.24 × 0.69	2.05	*1* and *2*—0.17, *2* and *3*—0.28
	2	36.71 × 0.46	0 (earthed)	
	3	47.04 × 0.34	2.05	
	4	9.69 × 3.52	39.40	
	5	46.73 × 5.68	2.36	
	6	13.95 × 0.20	2.36	
	7	39.60 × 5.80	2.36	
	8	14.74 × 0.25	27.22	

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 filters, which are listed in Table 3 for the 3D model.

From Fig. 3, it can be seen that the investigated constructions show a reasonably good agreement of the calculated AFCs of filters with the measured ones (Fig. 3). The filters have high frequency-selective properties and relatively small losses of the microwave

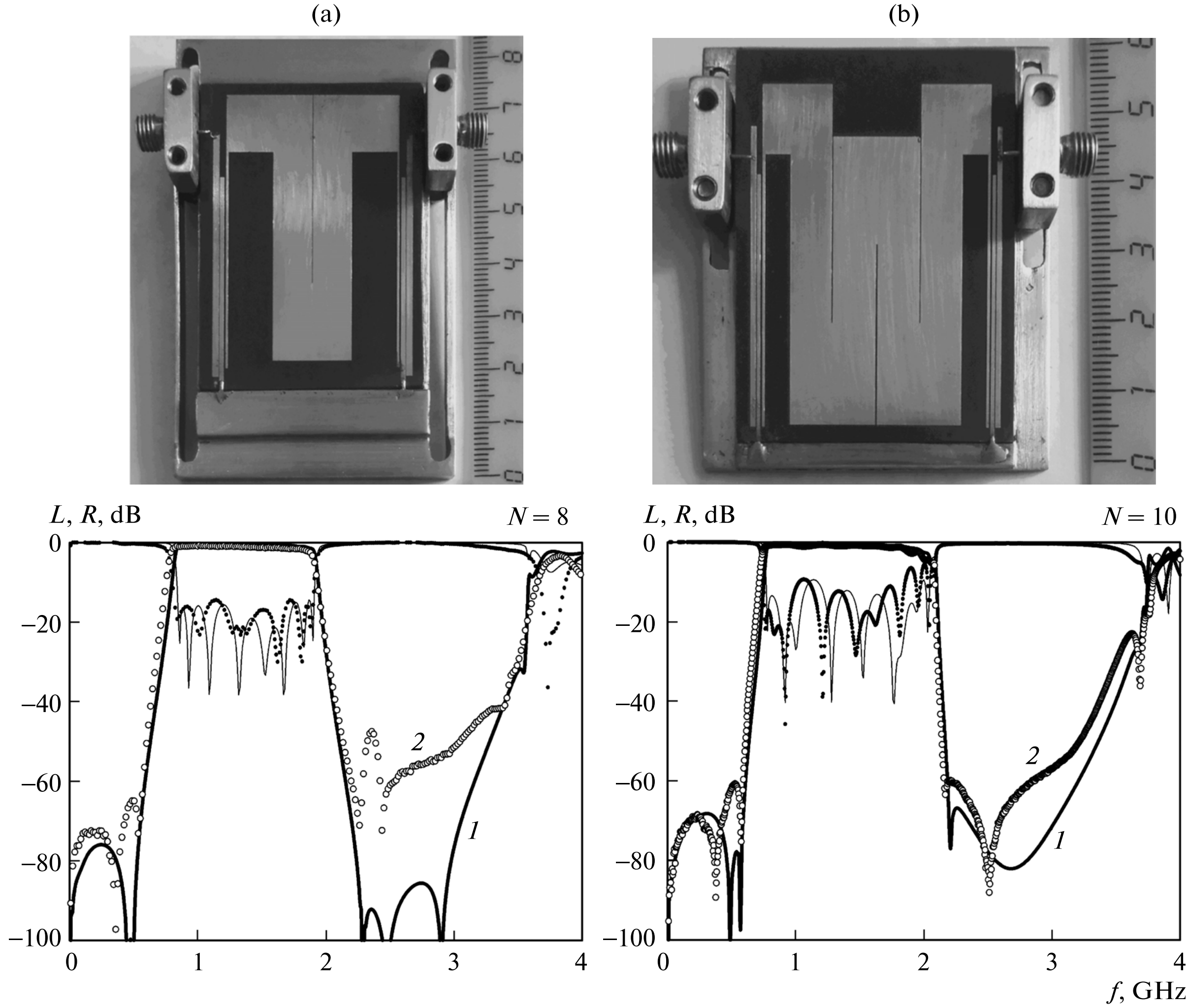

Fig. 3. AFCs of filters of the eighth (a) and tenth (b) orders. Lines (*1*) are the calculation, and points (*2*) are the measurements. In the insets we show the photographs of fabricated samples.

power in the passband: ~0.8 dB for the eighth-order filter and ~0.7 dB for the tenth-order filter, and also a wide relative passband.

Thus, we proposed and investigated new microstrip constructions of wideband bandpass filters of the fourth to tenth orders. In each of the investigated filters, one multimode resonator is used, the strip conductor in which has the shape of an irregular meander and electromagnetically coupled with the single-mode quarter-wave resonators at the input and output of the device. For the first time, the possibility of coincidence of eigenfrequencies up to the six lowest modes of oscillations, which participate in formation of the passband, is shown for the multimode resonator. The measurements of characteristics of preproduction models of filters of the eighth and tenth orders showed good coincidence with the results of the numerical electrodynamic analysis of devices using the 3D models. Due to the attenuation poles existing near the passband, the investigated constructions differ in reasonably wide stop bands with a high suppression level of the microwave power in them instead of only in an increased steepness in the AFC slopes.

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