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A New Design of a Miniature Filter on Microstrip Resonators with an Interdigital Structure of Conductors

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Abstract—A microstrip bandpass filter of new design based on original resonators with an interdigital structure of conductors has been studied. The proposed filters of third to sixth order are distinguished for their high frequency-selective properties and much smaller size than analogs. It is established that a broad stop band, extending up to a sixfold central bandpass frequency, is determined by low unloaded Q of higher resonance mode and weak coupling of resonators in the pass band. It is shown for the first time that, as the spacing of interdigital stripe conductors decreases, the Q of higher resonance mode monotonically drops, while the Q value for the first operating mode remains high. A prototype fourth-order filter with a central frequency of 0.9 GHz manufactured on a ceramic substrate with dielectric permittivity $\varepsilon = 80$ has microstrip topology dimensions of $9.5 \times 4.6 \times 1$ mm^3. The electrodynamic 3D model simulations of the filter characteristics agree well with the results of measurements.

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Development of modern systems of communications, radiolocation, radio navigation, and radioelectronic warfare poses increasing requirements for the characteristics of frequency-selective microwave devices, in particular, bandpass filters. In designing new filters, developers pay the main attention to increasing their selectivity, decreasing their dimensions, improving technology, and reducing cost of production. On the whole, these requirements are met by the traditional microstrip filter design, which is still rather widely used in modern microwave electronics [1, 2]. However, sometimes the main point in a required technical solution is related to further miniaturization of filters without deterioration of their selectivity. Solving this problem encounters considerable difficulties in the range of ultrahigh and, especially, very high frequencies.

The problem of microstrip filter miniaturization can partly be solved by folding regular strip conductors into hairpin [3], C-shaped [4], or rectangular spiral [5] structures or by using resonator strip conductors of stepped width [6]. However, it should be noted that almost all of these approaches to miniaturization lead to a decrease in the unloaded Q values of resonators used in these filters and, hence, to deterioration of their frequency-selective properties. High Q factors of microstrip resonators can be achieved with their conductors made of high-temperature superconducting materials [7], but the high cost of these devices and the ability to operate only at cryogenic temperatures restrict their wide practical use.

In recent years, new designs of miniature microstrip filters based on dual-regime resonators with split strip conductors [8], suspended resonators on substrates with a two-sided pattern of microstrip conductors [9, 10], and resonators formed by three parallel conductors on a two-layer hybrid suspended substrate [11] have appeared. In this way, it is possible not only to reduce filter dimensions more than ten times, but also to significantly increase their selectivity due to cross coupling between nonneighboring resonators [12]. It is important to note that, although filters on suspended substrates are more difficult to fabricate than are the typical microstrip structures, a two-layer suspended design can be implemented in monolithic structures [13] using the technology of multilayer integrated circuits based on low-temperature cofired ceramics.

In the present work, we have studied a new microstrip structure, which can be used to create multipole miniature bandpass filters possessing high frequency-selective properties. The proposed device employs original resonators with a interdigital structure of microstrip conductors formed on the top side of a dielectric substrate, which are distinguished from analogs in the fact that both bases of the interdigital structure are connected along the entire width to a screen—the bottom metal-coated side of the substrate [14]. The inset to Fig. 1 shows an example of the topology of a third-order filter with an interdigital structure of each resonator consisting of seven pins. It should be emphasized that each element of the interdigital structure represents a resonator with resonance frequency f_0 determined by the strip length and the dielectric permittivity of the substrate. However, due to a strong electromagnetic interaction between these resonators (which is related to small gaps between the microstrip conductors), their resonance frequencies exhibit strong repulsion. As a result, the lowest first mode of the multistrip resonator has a resonance frequency $f_1 \ll f_0$ [14]. For this reason, the dimensions of a multipole filter with the pass band determined by the lowest mode resonances of interacting resonators can be significantly reduced, which is the first important advantage of the filter design under consideration.

The second advantage of the proposed filters based on multistrip resonators is their broad high-frequency stop band, which is related to the coupling between resonators at higher stop frequencies being much weaker than on the first operation mode. This circumstance is due to the fact that high-frequency currents on the first resonance frequency are in-phase, whereas the currents at higher resonance frequencies in all or some pins (depending on the mode number) are counter-phase. This is illustrated in Fig. 1, which shows the frequency responses of bandpass filters with various numbers of resonators (n = 3–6) calculated in the framework of electrodynamic 3D model simulation. The filters were based on plates of TBNS ceramics with relative permittivity $\varepsilon = 80$, a thickness of 1 mm, and an area of 7.6×4.6 mm^2 for $n = 3$ and 17.7×4.6 mm^2 for $n = 6$. The strip width in the interdigital structure of seven pins was 120 μm and the gap between elements was 20 μm wide. The filters have the central bandpass frequency corresponding to the lowest mode resonance (f_1 = 0.9 GHz) with a relative bandwidth of 10% (at –3 dB from minimum loss level). The stop band width exceeded $3f_1$ on a level of –30 dB for the third-order filter, almost –50 dB for the fourth-order filter, almost –55 dB for the fifth-order filter, and more than –65 dB for the sixth-order filter.

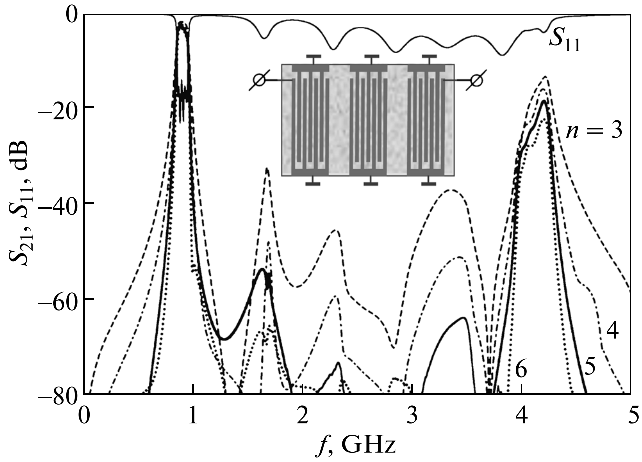

Fig. 1. Frequency responses of multipole (n = 3–6) filters based on multistrip resonators (N = 7) simulated using an electrodynamic 3D model. The inset shows the third-order filter design.

It is important to note that, at higher resonance frequencies of the resonators, there is a decrease in reflection losses related the absorption of microwave power in multistrip resonators. This is evidenced by the $S_{11}(f)$ curve, which is presented in Fig. 1 for the fifth-order filter only not to overload the picture. However, at frequencies above the pass band, this dependence remains almost unchanged for any number of resonators, which can be readily explained. Indeed, each resonator in these filters consists of seven elements forming the interdigital structure and, hence, has seven lowest oscillation mode, with a single antinode of high-frequency current and a single antinode of high-frequency voltage over the length of each microstrip conductor. The first mode resonance is involved in the formation of a pass band, while the resonances of the other six mode falling in the stop band effectively absorb the incident microwave power as confirmed by the minima of reflection losses at these frequencies in the $S_{11}(f)$ curves. Note that the parasitic pass band with a central frequency above $4f_1$ is formed by the resonances corresponding to mode for which there are two antinodes of high-frequency current and two antinodes of high-frequency voltage over the length of each microstrip conductor.

As is well known, one of the most important characteristics of resonators is their unloaded Q value, which primarily determines the level of microwave power losses in the pass band. An analysis of this value for the first mode (Q_1) as the function of design parameters of a multistrip resonator with interdigital conductors was carried out in [14]. It was established, in particular, that Q_1 increases in proportion to the square root of the number (N) of pins in the interdigital structure. However, in filters design based on these resonators it is also important to know how their parameters influence the unloaded Q values for higher regimes, since these resonance modes fall into the high-frequency rejection band and affect the level of microwave power suppression in this band.

Figure 2 shows the dependences of unloaded Q for resonances of the first three mode on gap width S between microstrip conductors in a seven-element interdigital structure on 1-mm-thick substrate made of TBNS (strontium-doped barium niobium titanate) ceramics with $\varepsilon = 80$. Note that, as gap width S decreases, the first mode resonance frequency decreases by about 30%. For this reason, the Q_1 value was calculated at a fixed resonance frequency of 1 GHz, which was maintained constant by varying the resonator length. As can be seen, the unloaded Q_1 for

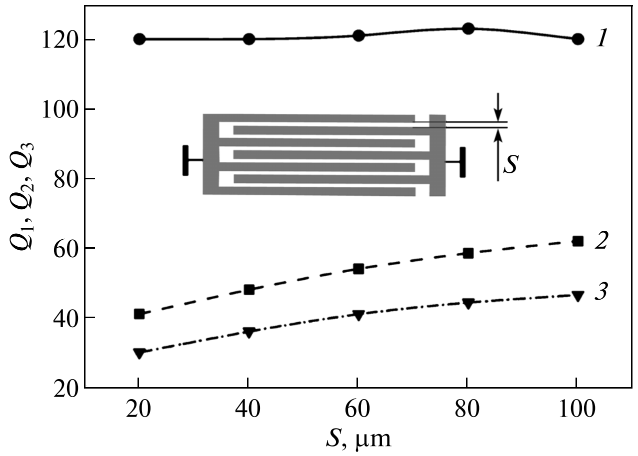

Fig. 2. Plots of unloaded Q values of the first three mode of a multistrip resonator ($N = 7$) vs. gap width S between strip conductors in the interdigital structure.

the first mode resonance remains almost unchanged irrespective of the gap width, while Q_2 and Q_3 grow with increasing S. However, the Q_2 value even at maximum gap remains half the value of Q_1 and Q_3 remains three times smaller than Q_1. This result implies that the coupling between resonators at higher resonance frequencies is weak, thus increasing both the width of the high-frequency rejection band and the level of microwave power damping in this band.

For experimental verification of the obtained results, we have simulated and then manufactured a prototype fourth-order filter based of microstrip resonators with $N = 7$ pins in the interdigital structure. Figure 3a shows a photograph of this filter brazed to a brass base plate, and Fig. 3b presents the frequency response of this device. The substrate material was TBNS ceramics ($\varepsilon = 80$) with a thickness of 1 mm and lateral dimensions 9.5 × 4.6 mm^2. The width of each resonator was 0.96 mm at a strip conductor width of 120 μm and a gap width of 20 μm between conductors. The spacing in terminal pairs of resonators was 1.12 mm, while the central pair was spaced by 1.46 mm. The central bandpass frequency was $f_1 = 0.9$ GHz, the relative bandwidth was 20%, and the level of losses in the pass band did not exceed 1.7 dB. The high-frequency rejection band on a –40 dB level extended up to $6f_1$.

Thus, we have proposed and studied a microstrip bandpass filter of original design based on resonators formed by stripe conductors comprising an interdigital structure with bases shortened to a screen. The filter is distinguished by its miniature size, broad rejection band, and simplicity of manufacturing technology. A prototype sample of the fourth-order filter exhibited high frequency-selective properties and showed good agreement between measured characteristics and those determined by 3D model electrodynamic numerical simulation. The obtained results confirm the good prospects of using the proposed filter design in devices for modern systems of communications, radiolocation, radio navigation, and radioelectronic warfare.

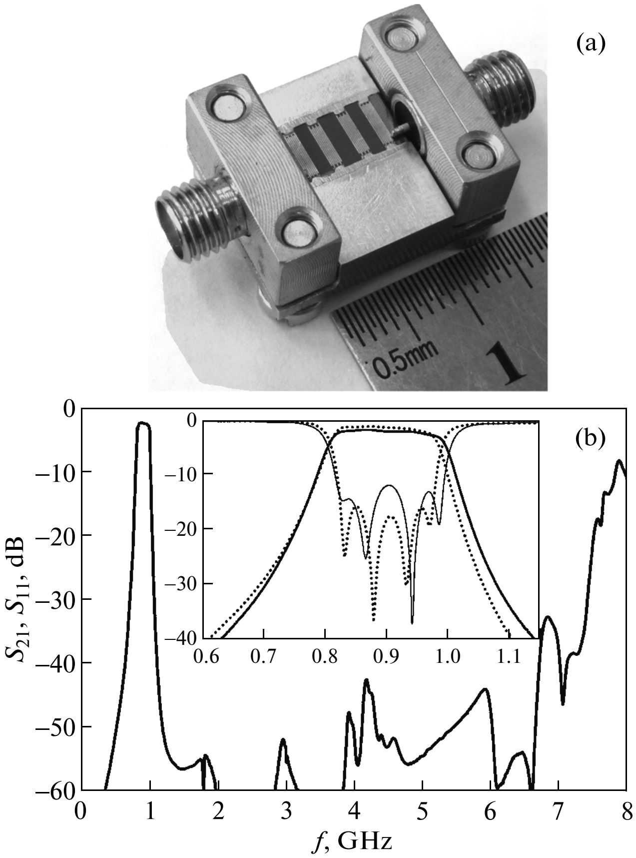

Fig. 3. Prototype sample of miniature fourth-order bandpass filter: (a) photograph; (b) frequency response; solid curves show the results of measurements, while dotted curves present the results of numerical simulations.

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