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A high-selectivity waveguide bandpass filter with interference suppression by more than 120 dB in rejection band

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The design of a 10th-order waveguide bandpass filter with an additional inductive cross-coupling between non-adjacent resonators has been proposed and studied. An inductive coupling is formed by a U-shaped conductor structure with grounded ends that is formed in the filter cover. This method of cross-coupling organization ensures not only the temperature stability of the characteristics, but also the manufacturability of the structure. The high selectivity of the device is achieved by both the attenuation poles located near the passband, as well as the level of suppression in the stopbands, exceeding 120 dB. The passband loss of the fabricated filter is ~ 0.8 dB at its central frequency $f_0 = 18.2$ GHz and relative bandwidth $\Delta f/f_0 = 1.5\%$. The small dimensions $(135 \times 30 \times 10\,\text{mm})$ and the weight of about 200 g of the device, with simultaneously high electrical characteristics show the promise of its use, for example, in on-board and ground-based space communication systems

Keywords: bandpass filter, waveguide, resonator, cross-coupling.

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Microwave filters having a narrow passband with steep slopes are needed to separate closely spaced channels in satellite communication systems [1]. These devices should also be compact, feature minimum insertion loss, and ensure stability of characteristics under temperature variations. In order to steepen the slopes of the passband, one is usually raise the number of resonators in a filter. However, this leads to an increase in size and in insertion losses in narrow bandpass devices if the unloaded Q0-factor of resonators is insufficient. Microstrip resonators with conductors made of superconducting materials are known to be compact and have a high Q0-factor [2], but their applicability is limited by a high cost and the need to maintain cryogenic temperatures.

Additional cross-coupling between non-adjacent resonators, which induces the formation of attenuation poles at the frequency response of a filter [3,4], helps to enhance the selectivity of a filter without increasing the number of resonators. This approach is used to improve the characteristics of devices with microstrip [4], coaxial [5,6], and waveguide [7] resonators and in filters based on quasi-lumped inductive L and capacitive C elements [8]. The steepest passband slopes are formed when attenuation poles are positioned symmetrically to the left and to the right of the passband. This is achieved by introducing additional capacitive cross-coupling either between the input and the output resonators in a four-resonator design [3] or between the second and the fifth resonators in a sixth-order filter [3,4].

Air-filled resonators, which are used widely in waveguide filters of centimeter and millimeter wavelength ranges, have a high unloaded Q0-factor, and an coupling iris in the broad wall of a rectangular waveguide provides the easiest way to introduce additional capacitive cross-coupling in such devices [7]. However, the two-level positioning of resonators in this design complicates the fabrication procedure. Therefore, a metal pin with open-circuited ends, which passes through a hole in a metal wall between resonators and is secured at its central part with a dielectric bead [8], is often used to establish capacitive cross-coupling between non-adjacent resonators. Unfortunately, this design also has certain technological flaws and requires the use of thermally stable dielectric materials; in addition, pin resonances reduce attenuation in stopbands, thus affecting negatively the frequency selective characteristics of a filter. These disadvantages may be rectified almost completely in a waveguide filter [9] with an additional cross-coupling element in the form of a U-shaped conductor with grounded ends. However, only third- and fourth-order filters, which have a low attenuation level in stopbands and are thus unsuitable for communication systems, were examined in [9].

In the present study, the indicated approach is analyzed with the use of equivalent circuits; in addition, a design concept for better manufacturability and temperature stability of characteristics of such bandpass filters (including high-order ones) is proposed. Parametric synthesis of a tenth-order filter is performed based on electromagnetic analysis of its 3D model in CST Studio Suite.

Figure 1, a shows the equivalent circuits of three fourth-order waveguide filters with resonators arranged sequentially and interacting via inductive irises in the narrow wall

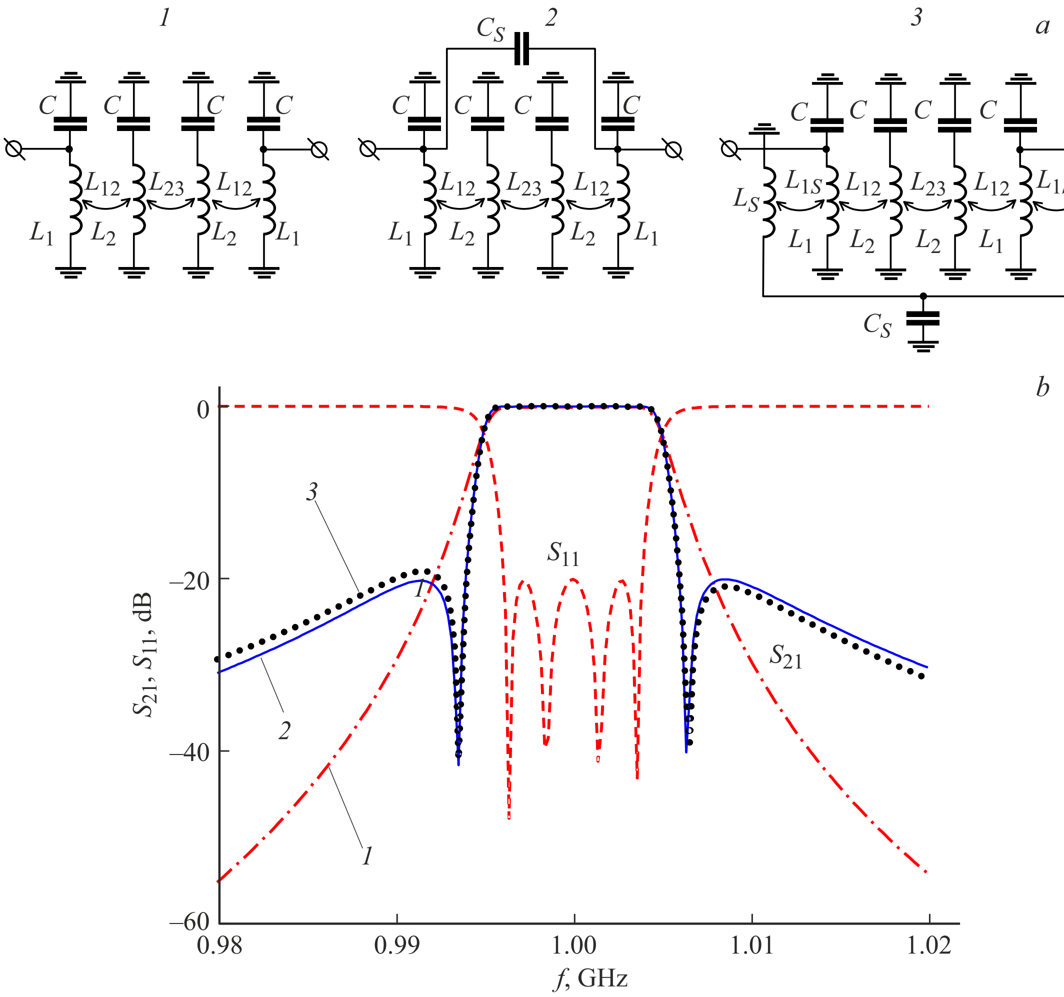

Figure 1. Air-filled resonators, which are used widely in waveguide filters of centimeter and millimeter wavelength ranges, have a high unloaded Q0-factor, and an coupling iris in the broad wall of a rectangular waveguide provides the easiest way to introduce additional capacitive cross-coupling in such devices [7].

of a rectangular waveguide The first design (*1*) features no additional cross-coupling between the input and output resonators, the second design (*2*) has capacitive C_S cross-coupling, and cross-coupling in the third design (*3*) is implemented with the use of inductive L_S and capacitive C_S elements, which correspond to a *U*-shaped conductor with grounded ends. Figure 1, *b* presents the frequency response of equivalent circuits of filters with central frequency $f_0 = 1\,\text{GHz}$ of the passband and fractional bandwidth $\Delta f / f_0 = 1\%$. The maxima of return loss (S_{11}) in the passband were set to $-20\,\text{dB}$ in the process of tuning the filters. The parameters of elements of equivalent circuits are listed in the table. The resonator cross-coupling coefficients were calculated as

$$k_{12} = \frac{L_{12}}{\sqrt{L_1 L_2}}, \quad k_{23} = \frac{L_{23}}{L_2}, \quad k_S = \frac{L_{1S}}{\sqrt{L_S L_1}}, \tag{1}$$

where L_{12}, L_{23} are mutual inductances of the corresponding resonators and $L_{1S}$is the mutual inductance of the first resonator and the *U*-shaped conductor providing additional cross-coupling.

It can be seen that additional cross-coupling induces the formation of attenuation poles (zeros of transmission coefficient S_{21}) near the passband, thus steepening the slopes of the passband considerably. Notably, capacitive (curve *2*) and inductive (curve *3*) cross-couplings produce almost the same effect. It is evident that two channels of signal transmission form in circuits with additional cross-coupling and waves of equal amplitudes are combined in antiphase at the frequencies of transmission zeros. Within this context, let us examine the frequency dependences of the transmission coefficient and the phase of a transmitted wave for three designs in a wide frequency range (Fig. 2) to find an explanation for the equivalence of circuits *2* and *3* (Fig. 1, *a*). It can be seen that the phase of a transmitted wave in the design without additional cross-coupling (curve *1*) remains close to 90° throughout the entire frequency band, with the sole exception being the passband. Therefore, the transmission coefficient is induc-

Nominal parameters of elements of equivalent filter circuits

Filter type	C, pF	L_1, nH	L_2, nH	$k_{12} \cdot 10^{-3}$	$k_{23} \cdot 10^{-3}$	C_S, pF	L_S, nH	$k_S \cdot 10^{-3}$
1	381.55	0.06639	0.066395	7.085	5.441	–	–	–
2	362.706	0.06964	0.06984	6.914	7.018	1.041	–	–
3	360.55	0.07067	0.07026	6.916	7.034	1081.65	0.0706	54.3

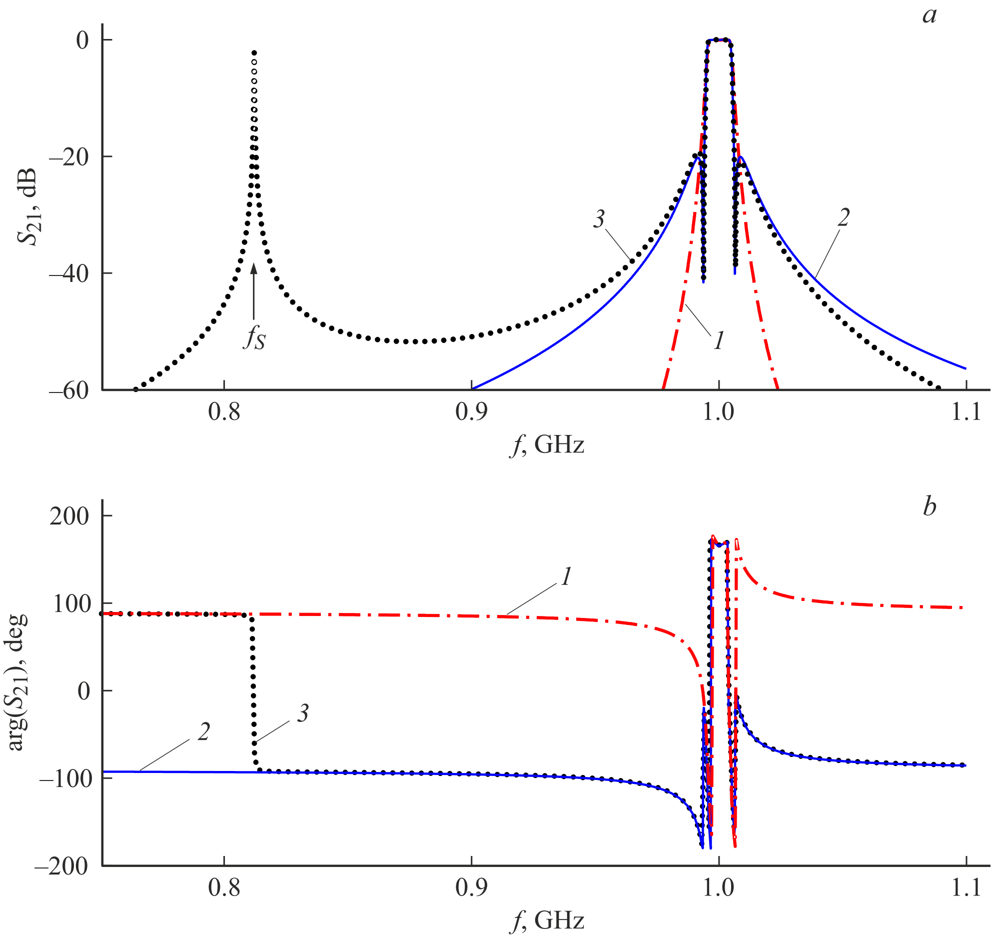

Figure 2. Frequency dependences of transmission coefficient S_{21} (a) and the phase of a transmitted wave (b) for the considered equivalent circuits.

tive in nature. The traditional filter design with additional capacitive cross-coupling (curve *2*) is also characterized by a phase of a transmitted wave that remains close to -90° throughout the entire frequency band, with the sole exception being the passband. Therefore, the transmission coefficient is capacitive in nature. The design with additional cross-coupling established by a U-shaped conductor with grounded ends (curve *3*) features a well-pronounced resonance of this conductor at frequency f_S below the passband. The frequency dependence of the phase of a transmitted wave indicates that the transmission coefficient is inductive in nature at frequencies below this resonance and capacitive (just as the coefficient characterizing circuit *2* in Fig. 1, a) at frequencies above it. This is the reason why the frequency response agree closely in the passband of designs *2* and *3* (curves *2* and *3* in Fig. 1, b).

It is known that fourth-order filters are not practically relevant to modern communication systems. Therefore, a tenth-order filter based on sections of a air-filled rectangular waveguide with a 10.5×6.5 mm cross section, wherein resonators interact via inductive irises in the narrow wall, was fabricated for experiments. The structural parameters of this filter were determined beforehand in the course of electromagnetic analysis of 3D model (upper panel in Fig. 3, a) in CST Studio Suite with preset central frequency $f_0 = 18.2$ GHz of the passband, its fractional bandwidth $\Delta f / f_0 = 1.5\%$ measured at -1 dB, and return loss (no greater than -20 dB). A U-shaped conductor with grounded

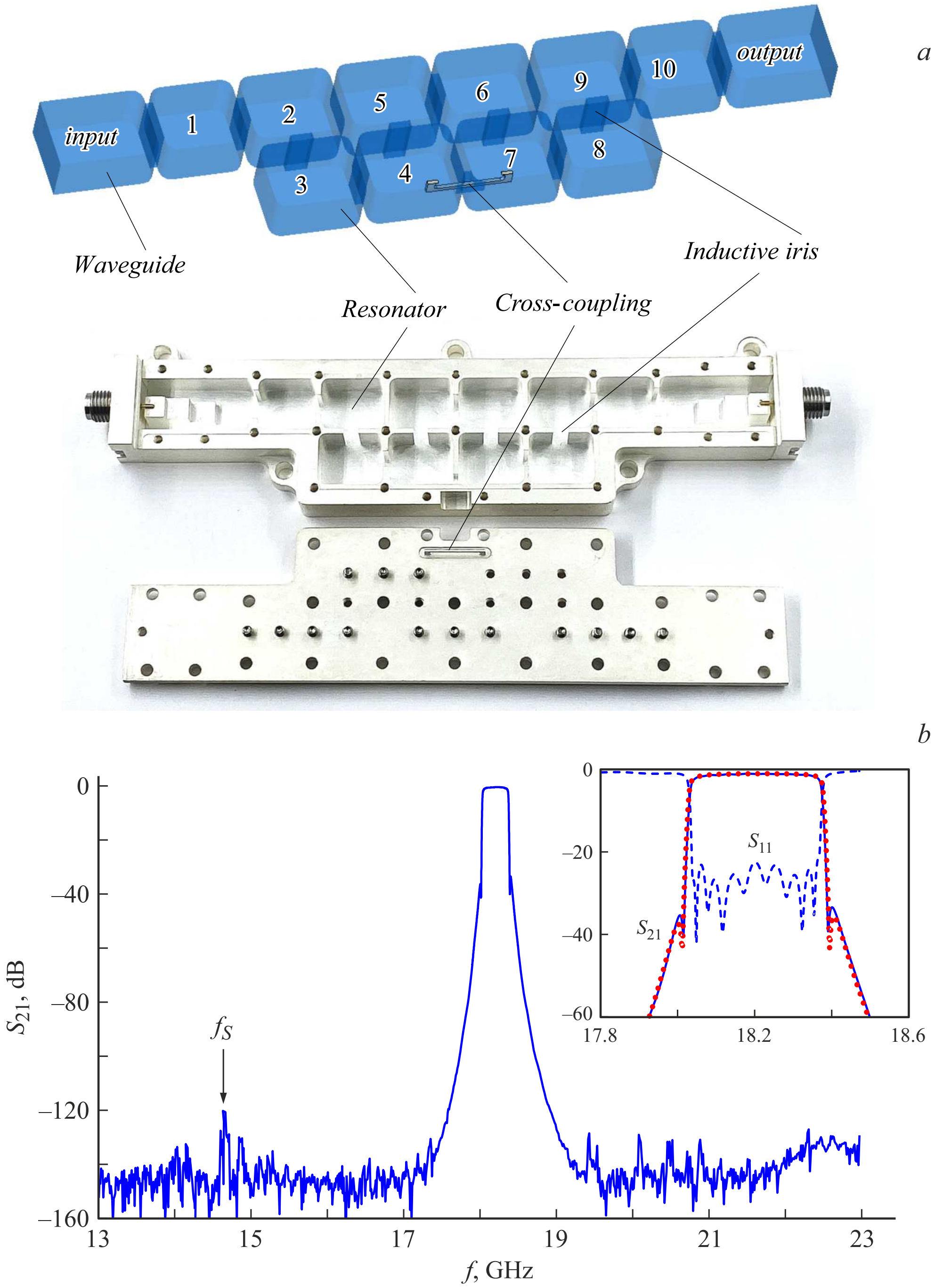

Figure 3. *a* — 3D model of a filter (top) and its photographic image with the cover removed (bottom); *b* — measured frequensy responses in wide and narrow frequency bands (curves) and calculation results (points).

ends in the cover of the case provides additional cross-coupling between the fourth and the seventh resonators. Oscillations type H_{101} shape the passband of the filter, and its middle part is made serpentine to reduce the filter length and make it easier to introduce additional cross-coupling. Coaxial connectors at the input and the output of the filter are matched to the waveguide transmission line by step transformers, and screws, which are seen clearly in the case cover in the photographic image of the filter (lower panel in Fig. 3, *a*), are used for adjustment. The case is made of Invar35 with a record-low thermal expansion coefficient and coated with a layer of silver with a thickness of 6 μm. Owing to this, the filter parameters remain almost unchanged within a temperature interval from −45 to +60°C.

The measured frequency response of S_{21} and S_{11} of the fabricated filter, which are represented by curves in Fig. 3, *b*, agree closely with the calculated data (points). The minimum insertion loss in the passband is 0.8 dB, and the return passband loss does not exceed -21 dB. Fine interference suppression in the stopbands (at a level above 120 dB) is one of the advantages of the designed filter. Note that the resonance of a U-shaped conductor with grounded ends in the considered filter is observed at $f_S \approx 14.7$ GHz. It is seen clearly in frequency response only when the number of resonators in the circuit is low; as the filter order increases, the resonance vanishes gradually. In the designed tenth-order filter, this resonance is manifested at a level below -120 dB.

The steepness of low-frequency (k_l) and high-frequency (k_h) slopes of the passband is an important parameter characterizing the frequency selective characteristics of bandpass filters. These coefficients are easy to calculate using the following formulae [10]:

$$k_l = \frac{\Delta f/2}{\Delta f_{30}^{l} - \Delta f/2}, \qquad k_h = \frac{\Delta f/2}{\Delta f_{30}^{h} - \Delta f/2}, \tag{2}$$

where Δf_{30}^{l} and Δf_{30}^{h} are frequency bands measured from the central frequency to low-frequency and high-frequency slopes at a level of -30 dB. These coefficients for the proposed filter design turned out to have similar values: $k_l = 9.6$ and $k_h = 11$. This confirms that the device has high selectivity characteristics.

Thus, owing to the presence of two attenuation poles at the frequency response located symmetrically with respect to the center of the passband, the designed tenth-order waveguide bandpass filter with additional inductive cross-coupling between non-adjacent resonators provides a high level of interference suppression in the stopbands and high selectivity. The frequencies of attenuation poles may be adjusted by varying the strength of additional cross-coupling that is set by the position of a metal screw on the side wall of the filter case at the central part of a U-shaped conductor with grounded ends. Thus, one may shift transmission zeros to the required frequencies without altering the passband parameters.

It was demonstrated that additional capacitive cross-coupling, which is traditionally used in multisection filters, is equivalent at frequencies in the passband region to additional inductive cross-coupling introduced by a U-shaped conductor (if the eigen resonance frequency of this conductor is positioned below the passband). It is important to note that the filter design is simplified considerably if additional inductive cross-coupling is used, since it does not require dielectric beads to secure an element providing additional capacitive cross-coupling within the filter case. The lack of dielectric elements naturally makes a filter more thermally stable. In addition, the proposed design offers high manufacturability, since a U-shaped conductor with grounded ends is integrated into the filter case cover, thus providing sufficient rigidity and vibration resistance and, as was already noted, fine thermal stability of operating parameters.

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Conflict of interest

The authors declare that they have no conflict of interest.

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