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INVESTIGATION OF THE SPECIAL FEATURES OF THE COUPLING COEFFICIENTS FOR MICROSTRIP ASYMMETRIC HAIRPIN RESONATORS AT FREQUENCIES OF THE SECOND PASSBAND

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The behavior of the frequency-dependent coupling coefficients is investigated for a pair of microstrip resonators formed by conductors shaped as an asymmetrical hairpin. It is demonstrated that the total coupling coefficient of the resonators in a two-pole filter becomes close to zero in the region of the frequency of the second resonance due to mutual compensation for inductive and capacitive interactions. This allows a device for protection against high-power radio pulse to be developed based on such resonators with additional hairpin resonator containing control element manufactured from high-temperature superconductor (HTS) film.

Keywords: microstrip resonator, high-temperature superconductor, inductive and capacitive interactions, coupling coefficient, frequency response.

High-speed power limiters – protection devices (PD) – are necessary to protect input receiver circuits from high-power radio pulses. It is obvious that the electric PD strength is determined by the portion of power absorbed by the device from that incident on its input. Therefore, in addition to high speed, such devices must also possess high reflectivity in the off-state of the device. Microstrip resonant structures whose control element is manufactured from a high-temperature superconductor (HTS) film are promising for such devices actively investigated nowadays [1–3]. The high speed of these protection devices is caused by small times of phase transition of the HTS material from the superconducting to normal state when current exceeding the critical threshold flows through it. The high reflectivity of the device in the off-state is caused practically by broken coupling between its input and output when the state of the HTS film changes from superconducting to normal one.

The principle of PD operation consists in the following. The third resonator with the strip conductor completely or partially manufactured from the HTS material film is added to two microstrip resonators (MSR) with configurations of the conductor strips that provide mutual compensation for the inductive and capacitive interactions near resonant frequencies [4]. This resonator provides required coupling between the MSR, thereby forming the desired passband of the device. When the HTS film goes to the normal (high-resistance) state under the influence of a radio pulse of sufficient power, coupling between the resonators is broken, and the device operates in the regime of limitation. The level of signal suppression in the limitation regime is one of the main specifications of protection devices. As demonstrated investigations [3], this level decreased with increasing central frequency of the working band of the device. In many respects, this is due to a decrease in sizes of resonators and devices as a whole accompanied by a decrease of the distance between the input and output of the device and by the corresponding increase of the directly transmitted signal.

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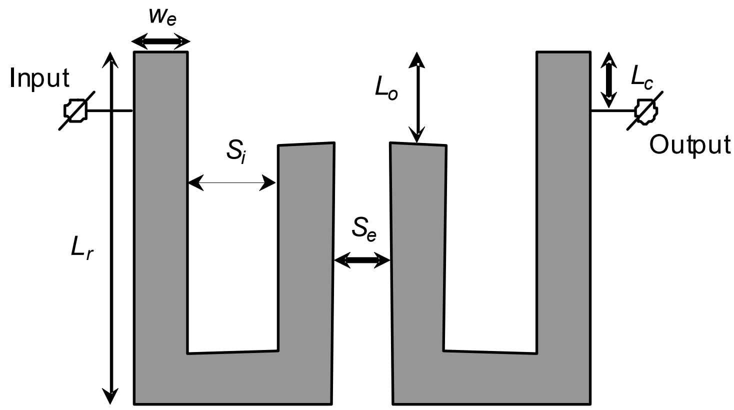

Fig. 1. Topology of conductors in the section of two asymmetrical hairpin MSR.

One of the obvious methods of increasing the resonator sizes consists in the application of resonances of their higher oscillation modes to form the desired working frequency band. Therefore, the problem of search for such configurations of the MSR strip conductors for which the capacitive and inductive interactions can be compensated at frequencies, for example, near the resonance of the second oscillation mode is urgent. The possibility of such compensation for a fixed length of coupling of the strip conductors in the pair of regular MSR was demonstrated in [5]. However, it is technically difficult to include the third resonator with the HTS element to implement coupling between all MSR in the given frequency band when designing protection devices based on the MSR with regular strip conductors.

In the present work, the frequency dependences of the coupling coefficients of the microstrip structure consisting of two resonators whose strip conductors are shaped as asymmetric hairpins (Fig. 1) are investigated. Such shape of the MSR conductors allows the third resonator with control HTS element to be easily connected. The research is aimed at determining the shape of conductors of the microstrip structure that provides the absence of MSR coupling at frequencies near the resonance of the second oscillation mode to design on its basis protection devices.

Let the strip conductors forming resonators in the design (Fig. 1) have the width w_e, internal hairpin gap be S_i, hairpin height be L_r, lengths of its strip conductors differ by L_o, gap between the strip conductors be S_e, and the distance from the resonator end to the point of conductive connection to external lines be L_c. Resonators are placed on the substrate with thickness h having dielectric permittivity ε.

The examined structure was analyzed numerically for a one-dimensional model consisting of regular sections of single and coupled microstrip lines connected in series into which the examined structure was subdivided. The parameters of these lines per unit length required to calculate the frequency response and to obtain the distribution of currents and voltages in the conductors were calculated in the quasi-static approximation with allowance for the end capacities. The microwave losses were taken into account by introducing the Q_0 factor determined experimentally.

To determine the frequency-dependent coupling coefficients, the modified energy approach [4] was used according to which the inductive, $k_L(f)$, and capacitive, $k_C(f)$, coupling coefficients of the microstrip resonators were expressed through the energy of electromagnetic oscillations in the microstrip structure and were calculated from the following formulas:

$$k_L(f) = \frac{2E_{12L}}{\left(E_{1L} + E_{1C} + E_{2L} + E_{2C}\right)} \frac{1}{K}, \tag{1}$$

$$k_C(f) = \frac{-2E_{12C}}{\left(E_{1L} + E_{1C} + E_{2L} + E_{2C}\right)} \frac{1}{K}, \tag{2}$$

where E_{1L} and E_{1C} are the energies of the magnetic and electric fields, respectively, stored by the first resonator and proportional to the squared current and voltage in the first strip conductor; E_{2L} and E_{2C} are the energies of the magnetic and electric fields, respectively, stored by the second resonator and proportional to the squared current and voltage in the second strip conductor; E_{12L} and E_{12C} are the energies of the magnetic and electric fields, respectively, stored by the first and second resonators mutually and proportional to the product of currents in the first and second strip conductors and to the product of voltages in them; $K = |U_{\text{out}}|/|U_{\text{in}}|$ is the magnitude of the voltage transmission coefficient from the input to the output of the microstrip structure. The energies of the magnetic and electric fields were calculated from the following expressions:

$$E_{1,2L} = \frac{1}{2}\int_0^{l_r} L_1 I_{1,2}(x) I^*_{1,2}(x)dx\,, \tag{3}$$

$$E_{1,2C} = \frac{1}{2}\int_0^{L_r} (C_1 + C_{12}) U_{1,2}(x) U^*_{1,2}(x)dx + \frac{1}{2}\int_{L_r}^{l_r} C_1 U_{1,2}(x) U^*_{1,2}(x)dx\,, \tag{4}$$

$$E_{12L} = \operatorname{Im}\int_0^{L_o} L_{12} I_1(x) I^*_2(x)dx + \operatorname{Im}\int_{L_o}^{L_r} L_{12} I_1(x) I^*_2(x)dx\,, \tag{5}$$

$$E_{12C} = \operatorname{Im}\int_0^{L_o} C_{12} U_1(x) U^*_2(x)dx + \operatorname{Im}\int_{L_o}^{L_r} C_{12} U_1(x) U^*_2(x)dx\,, \tag{6}$$

where $I_{1,2}$ and $U_{1,2}$ are the complex currents and voltages in the conductors of the first and second resonators, L_1 and C_1 are the inductance and capacitance per unit length of the single microstrip line; L_{12} and C_{12} are the mutual inductance and mutual capacitance of the coupled microstrip lines; and $l_r = 2L_r + S_i - L_o$ is the total length of the MSR strip conductor. The total coupling coefficient was calculated from the formula [6]

$$k = \frac{k_L + k_C}{1 + k_L k_C}\,. \tag{7}$$

Investigation of the behavior of the frequency-dependent coupling coefficients demonstrated that with increasing L_o and other parameters of the design remaining unchanged (see Fig. 1), the frequency at which the inductive and capacitive interactions were mutually compensated monotonically increased reaching the region of resonance of the second oscillation mode.

Figure 2 shows the dependences of the capacitive (the dotted curve), inductive (the dashed curve), and total (the solid curve) coupling coefficients of the asymmetric hairpin MSR on the distance between their conductors normalized by the thickness of the substrate. The curves were calculated for the resonant frequency of the second MSR oscillation mode using formulas (1)–(7) for the following parameters of the structure: alumina substrate ($\varepsilon = 10.6$), thickness h = 0.5 mm, width of the strip conductors forming the resonators $w_e = 0.4$ mm, $L_r = 5.01$ mm, $L_o = 3$ mm, and $S_i = 5.3$ mm.

It can be seen that the modulus of the total coupling coefficient $|k|$ behaves anomalously with increasing gap length. First it sharply decreased to zero at the point at which the moduli of the inductive and capacitive coupling coefficients were equal, and then increased reaching its maximum. And only with further increase in the gap length, its normal decrease was observed. As a result, the same $|k|$ value, for example, equal to 0.005 could be observed for three different gaps between the MSR conductors as well as for the pair of symmetric hairpins [4]; however, this was already at the resonant frequency of the second oscillation mode. From the figure it is also seen that at the point $S_e/h \approx 0.8$, the capacitive and inductive interactions are compensated, and $|k| = 0$. In this case, the attenuation pole located in the place of the second passband destroyed it, providing a high level of microwave power reflection from the input of the examined microstrip structure.

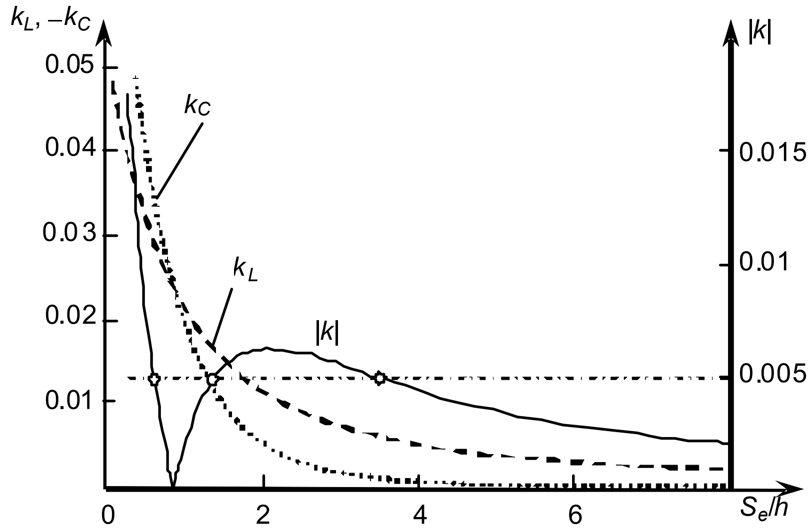

Fig. 2. Dependences of the coupling coefficients at the frequencies of the second passband of the two-section device on the gap between the resonators normalized by the substrate thickness.

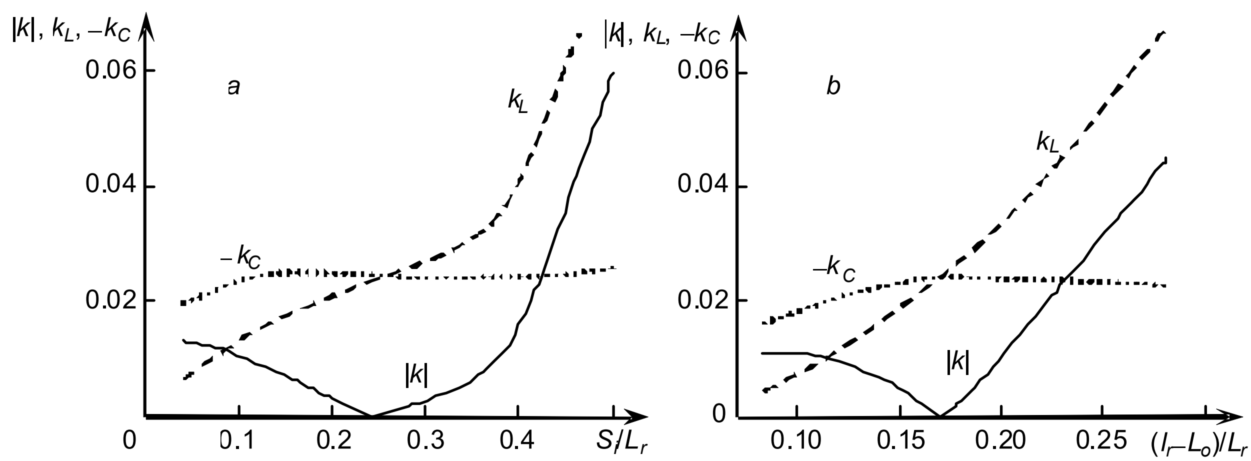

Fig. 3. Dependences of the coupling coefficients at the frequency of the second resonance of the microstrip structure: *a*) on the relative length of the internal gap of the asymmetric hairpin for $L_o = 2.5$ mm and *b*) on the relative length of the coupling length of the strip conductors for $S_i = 5.3$ mm.

It is obvious that the behavior of the inductive and capacitive MSR coupling coefficients is determined by the design parameters of the resonators and, in particular, by the relative length of the coupling region of their strip conductors. This fact is proved by the results of investigations shown in Fig. 3. The curves were drawn for the design parameters of the microstrip structure presented above at the resonant frequency of the second oscillation mode. It can be seen that the relative length of the coupling regions of the strip conductors influences weakly on the capacitive interaction of the resonators, but changes significantly the inductive interaction. Compensation for these interactions with zero total coupling coefficient is observed at points $S_i/L_r \approx 0.25$ (*a*) and $(l_r - L_o)/L_r \approx 0.17$ (*b*).

The frequency dependences of the total coupling coefficient of the resonators drawn for three gaps between the strip conductors are shown in Fig. 4*a*. The solid curve illustrates the case of compensation for the inductive and capacitive MSR interactions at the second resonant frequency $f_2 \approx 9$ GHz, the dashed curve is drawn for a smaller gap

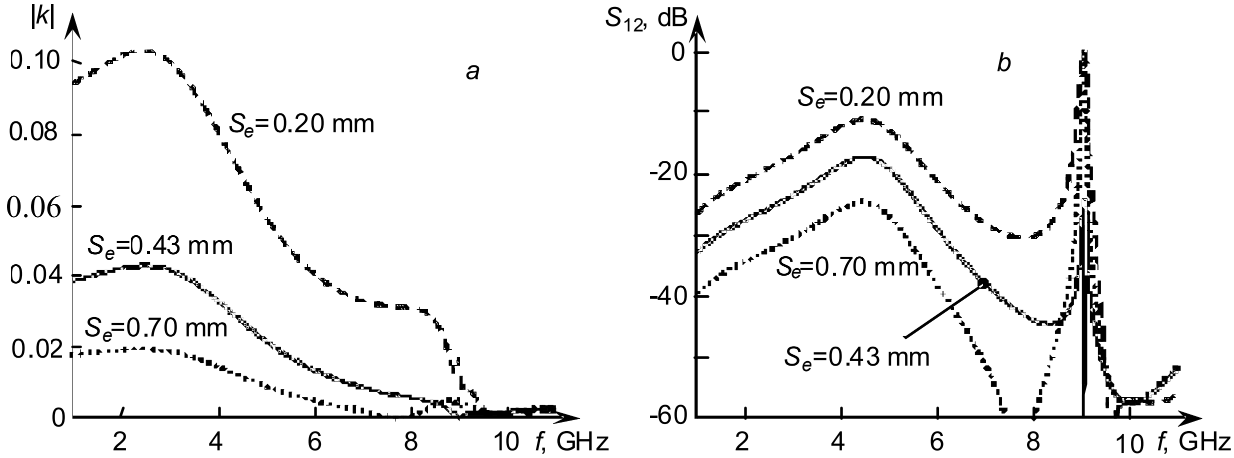

Fig. 4. Frequency dependences of the coupling coefficient of the two-section device for the indicated gaps between the resonators (*a*) and dependences of the transmission coefficients corresponding to them (*b*).

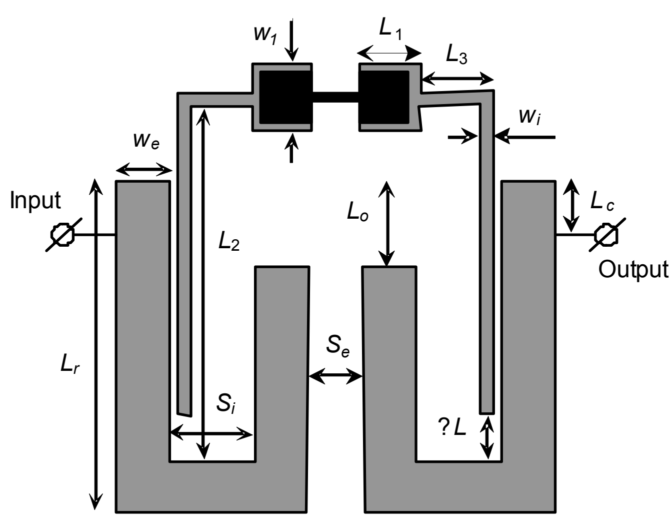

Fig. 5. Topology of the conductors of the device intended for protection against a high-power radio pulse.

between the conductors, and the dotted curve is drawn for a larger gap. Figure 4*b* shows the frequency response of the microstrip structure for the same gaps. It can be seen that the microwave power losses in the first passband ($f_1 \approx 4.5$ GHz) increase with the gap length, and in the second passband they are minimum only for the intermediate gap.

The results obtained allowed us to develop a device intended for protection against a high-power radio pulse (Fig. 5) in which the input and output resonators are shaped as asymmetric hairpins and the total coupling coefficient between these resonators is equal to zero. To form the working passband, the additional hairpin resonator with irregular strip conductor in the center of the gap of which the control element from HTS film shaped as a dumbbell is added to the design. It is important to note that the working oscillation mode of this resonator is the third mode such that the central region of the control element was in the antinode of the high-frequency current.

It is obvious that the passband width of the given design is determined by the interaction of the end resonators with the central resonator. The device operates as follows. When the input signal power is below the threshold, the HTS

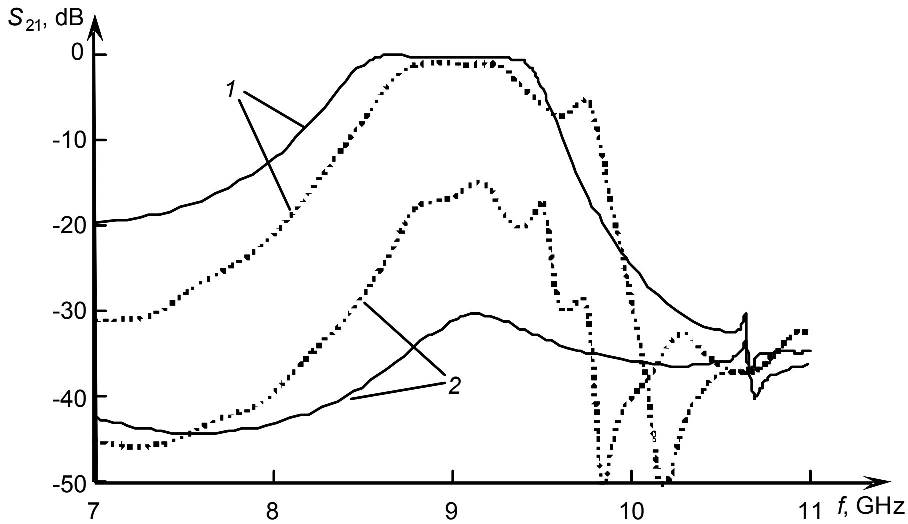

Fig. 6. Frequency dependences of the transmission coefficient of the protection device. Here curve *1* is for the on-state and curve *2* is for the off-state of the device. The solid curves are for the results of modeling, and the dotted curves are for the experimental data.

element is in the superconducting state, the Q-factor of the third resonator is maximal, and the device in this case represents the three-pole filter with small losses in the passband. If the signal power exceeds the threshold, the HTS film is converted into the normal (high-resistive) state, the Q-factor of the third resonator will decrease thereby breaking the coupling between the MSR and providing the regime of power limitation. It should be noted that the HTS element shaped as a dumbbell has capacitive rather than galvanic coupling with the conductors.

Using the topology of the conductors shown in Fig. 5, a prototype protection device was manufactured with the following design parameters: the alumina substrate with thickness of 0.5 mm (ε = 10.6), w_e = 0.4 mm, w_i = 0.2 mm, S_i = 4.3 mm, S_e = 0.7 mm, L_r = 6.2 mm, L_o = 3.75 mm, L_1 = 0.85 mm, L_2 = 6.25 mm, L_3 = 3.45 mm, and ΔL = 0.7 mm. The sizes of the wide and narrow parts of the HTS element were 1 × 0.6 mm and 0.1 × 0.9 mm, respectively. The YBaCuO HTS film with thickness of 0.08 μm was deposited on the $NdGaO_3$ substrate with thickness of 0.5 mm, and the surface resistance of the film in the normal state was 105 Ω/□. The system was cooled with liquid nitrogen.

Figure 6 shows the frequency dependences of the transmission coefficient of the developed model device. The solid curves here show the results of electromagnetic modeling using the program *Sonnet Lite*, and the dotted curves show experimental results. It can be seen that when the HTS element is in the superconducting state, which corresponds to the on-state of the device, it has the passband with fractional width of about 12% and the central frequency of about 9 GHz; in this case, losses in the passband are only 1 dB. When the HTS element is in its normal state corresponding to the off-state of the device, the transmission coefficient at the working frequencies decreases by about 20 dB. In comparison with the results of modeling, this figure is approximately by 10 dB less, which is explained by insufficiently good compensation for the inductive and capacitive interactions between the input and output resonators.

Thus, our investigations of the frequency-dependent coupling coefficients of the pair of microstrip resonators whose strip conductors are shaped as asymmetric hairpin have demonstrated the anomalous behavior of the total coupling coefficient versus the gap between the conductors observed at the frequency of the second resonance. In addition, it was demonstrated that the inductive and capacitive interactions of resonators were compensated at this frequency for a certain configuration of the strip conductors. For this reason, this structure can be used to develop a device for protection against a radio pulse. This ability was demonstrated experimentally for the prototype device in which the third hairpin resonator with control element based on the HTS film was used. The central frequency of the working band of the device was 9 GHz, and the fractional width was no less than 10%.

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