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Receiver Protecting Device Based on Microstrip Structure with High-Temperature Superconductor Film

B. A. Belyaev*, I. V. Govorun, A. A. Leksikov, and A. M. Serzhantov
Kirensky Institute of Physics, Siberian Branch, Russian Academy of Sciences, Krasnoyarsk, 660036 Russia
Reshetnev Siberian State Aerospace University, Krasnoyarsk, 660014 Russia
Siberian Federal University, Krasnoyarsk, 660041 Russia
**e-mail: belyaev@iph.krasn.ru*

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Abstract—New design of an effective device for protection against high-power electromagnetic pulses has been created based on a pair of noninteracting microstrip resonators, which are coupled in the working frequency band via a third resonator based on a thin film of high-temperature superconductor (HTSC) occurring in the superconducting state. Under the action of an electromagnetic pulse with the power above a certain threshold, the HTSC film element passes from the superconducting to normal (high-resistivity) state, thus breaking the coupling between resonators. This leads to power limitation at the device output due to a strong signal reflection from the input.

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As is known, devices of protection against high-power electromagnetic radiation (power limiters) are employed in radars for preventing the damage of input circuits by intrinsic probing electromagnetic pulses and for fighting with radar countermeasure systems. The most widely used microwave devices of this kind are semiconductor limiters [1, 2], but these sometimes do not meet modern requirements with respect to the electric strength and response speed. Quite good characteristics—short switching time, high level of power limitation, and high electric strength—is achieved with vacuum electron devices employing transverse electron bunching under cyclotron resonance conditions [3, 4]. The physical operation principles of these devices were considered in much detail in [5]. However, these devices are rather difficult to manufacture and adjust and they possess large weight and dimensions, in particular, because their operation requires high constant and homogeneous magnetic field.

The development of high-temperature superconductors (HTSCs), which are characterized by an extremely short time ($\sim 10^{-13}$ s) of the transition from the superconducting to normal state and by relatively high resistivity in the normal state, stimulated research for their possible use in the systems of protection against electromagnetic radiation. As a rule, the HTSC-based devices of this kind employ segments of strip, microstrip, or coplanar transmission lines matched with the tract, the conductors of which are made of HTSC materials [6]. The operation principle of these devices is obvious: should the transmitted signal possess a power at which the current density in the line exceeds a critical level, the material passes from the superconducting to normal (high-resistivity) state, which leads to limitation of the output power. However, almost all power not transmitted to the output is absorbed in the transmission line. For this reason, the electric strength of these devices is rather low, being determined primarily by the efficiency of heat removal from the system.

Previously, Kozyrev [7] described a system representing, in fact, a microstrip bandpass filter with the strip conductors of resonators made of an HTSC material. The operation principle of the proposed device is also quite evident: as the input signal power exceeds a certain level, the microwave current density in the conductor of the input resonator exceeds a threshold value for the given material and this conductor passes from the superconducting to normal state. As a result, the resonator Q sharply drops, while losses in the pass band of the filter sharply grow. However, our investigations [8] showed that a rather significant part of the input signal power is still absorbed in the input resonator rather than reflected, which decreases the electric strength of this device. Thus, a topical task consists in creating devices, in which maximum possible fraction of the incident signal power would be reflected from the input resonator upon the HTSC material transition to the normal state.

Recently we have patented devices [9] designed as two-resonator microstrip filters with a strip topology ensuring compensation of the inductive and capacitive

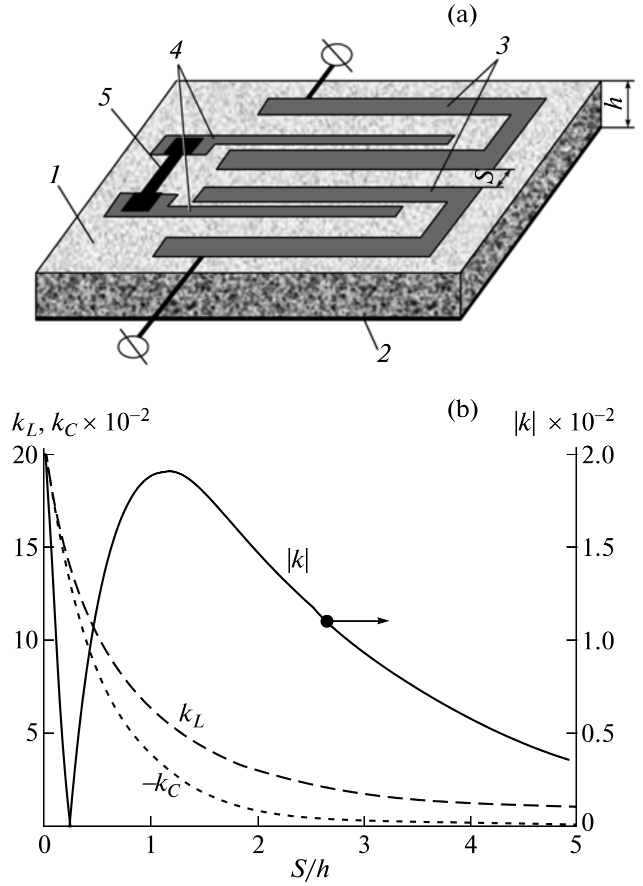

Fig. 1. (a) Schematic diagram of the receiver protecting device: (*1*) substrate; (*2*) bottom screen (grounded base); (*3*) strip conductors of side resonators with compensated coupling; (*4*) strip conductors of the central composite resonator; (*5*) film conductor of HTSC element. (b) Plots of the modulus of the total ($|k|$), inductive (k_L), and capacitive (k_C) coefficients of coupling between side microstrip resonators *3* on the distance *S* normalized to the substrate thickness *h*.

interaction of resonators at frequencies of the first transmission band. The transmission band is formed due to the coupling between resonators that is provided by an HTSC thin-film element in the form of a ring, which envelopes antinodes of the high-frequency currents of both resonators when the element occurs in the superconducting state. When a signal with power exceeding a certain threshold passes through this device, the HTSC element passes from the superconducting to normal (high-resistivity) state, thus breaking the coupling between resonators. As a result, the coefficient of microwave power transmission through the device drops by more than 20 dB, predominantly due to its reflection. However, since the coupling between resonators in this device decreases with increasing frequency, it is impossible to obtain the fractional bandwidth of working frequencies above 10% in the Gigahertz range.

This Letter describes a new original design of a microstrip device for receiver protecting with an HTSC thin-film element, which is free of the aforementioned disadvantage.

The proposed device represents essentially a three-unit microstrip filter (Fig. 1a) on substrate *1* the bottom surface *2* of which is completely metal-coated (grounded base). Conductors of the identical input and output (side) resonators *3* are made of a "normal": metal (copper) in the form of hairpin. The third (central) composite resonator *4* also has a hairpin shape and is made of copper, but its central part has a cut that is shunted by an HTSC film element *5*. A strip conductor of this element has a dumbbell shape and represents an YBaCuO layer deposited onto 0.5-mm $NdGaO_3$ substrate (not depicted in Fig. 1a). In addition, the HTSC film is protected from atmospheric factors by a thin dielectric film, so that the HTSC strip has no direct galvanic contact with side conductors *4* of the central resonator. However, the broad terminal pads of the dumbbell shaped HTSC element form rather large capacitance with copper strip conductors *4*, which ensures short circuit at microwave frequencies.

The device operation is based on an anomalous dependence of the total coupling coefficient at the first-mode frequency of hairpin comb-arranged resonators on the distance between their conductors [10]. This phenomenon was discovered for coupled dumbbell shaped resonators [11], which were used in the patented protection device [9]. Figure 1b shows plots of the modulus of the total coupling coefficient $|k|$ and the coefficients of inductive (k_L) and capacitive (k_C) coupling between hairpin microstrip resonators *3* on the distance *S* between their conductors normalized to the substrate thickness *h* [10]. The anomalous character of the total coupling coefficient $|k|$ consists in that, as the distance *S* increases, this coefficient initially sharply drops to zero at a certain gap width, then growth to reach a certain maximum, and eventually exhibits a normal monotonic decrease. Thus behavior is related to (i) the opposite signs of the coefficients of inductive (k_L) and capacitive (k_C) coupling between side resonators and (ii) their different dependence on distance *S*. For this reason, the two coefficients compensate each other at a certain *S* value. As a result, the coupling between two resonators in the microstrip structure vanishes and the its amplitude–frequency characteristic exhibits a damping pole instead of the first transmission band [10].

In the device under consideration (Fig. 1a), the gap width *S* between resonators *3* is selected so as to ensure that, in the absence of HTSC element *5*, the transmission of microwave power at frequencies in the region of the first mode of side resonators would be at minimum. In this case, the coupling between the input and output resonators is absent ($|k| = 0$). In the presence of the HTSC element in the superconducting state, the microstrip device is adjusted as a three-resonator filter on interdigital hairpin resonators, the pass band of which is determined by the interaction between the central and side resonators. It is important to note that, for the interdigital hairpin resonators, the capacitive and inductive interactions in the first band has the same sign and, hence, enhance each other [10]. A transition of the HTSC element from the superconducting to normal (high-resistivity) state "breaks" the central resonator, which leads to a significant suppression of coupling between the input and output resonators. As a result, the transmission coefficient of the device drops by several dozen decibels, predominantly due to the signal reflection from the input.

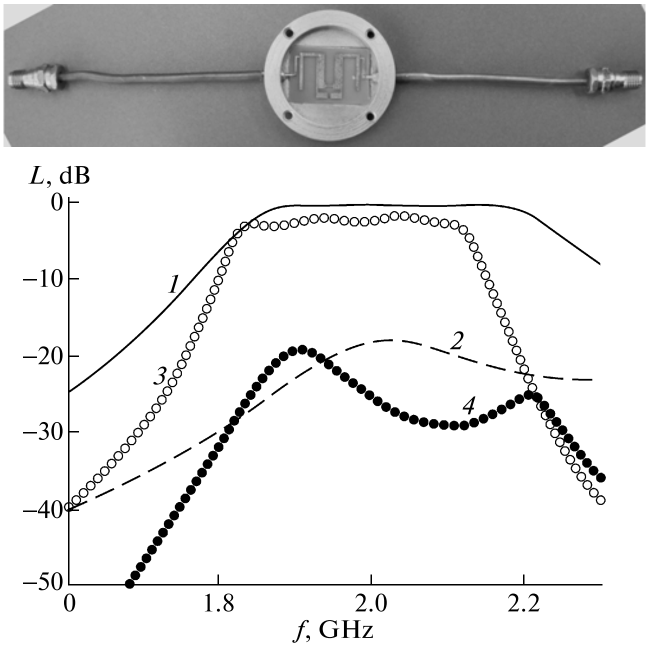

Fig. 2. Photograph of the prototype device and its amplitude–frequency characteristics in cases when the HTSC element occurs in the (*1*, *3*) superconducting and (*2*, *4*) normal state: (*1*, *2*) results of numerical simulation; (*3*, *4*) experimental data.

The above considerations are confirmed by the data presented in Fig. 2, which shows the amplitude–frequency characteristics of the proposed device in cases when the HTSC element occurs in the (*1*, *3*) superconducting and (*2*, *4*) normal state. The top inset shows a photograph of the prototype device. The microstrip structure was arranged on an 0.5-mm-thick polycor (alumina ceramics) substrate with a permittivity of $\varepsilon = 9.8$. The outer dimensions of the input and output resonators *3* (see Fig. 1a) in this device are 10.2 × 8.2 mm, the strip width of their conductors is 0.6 mm, and the gap width is $S = 2.8$ mm. The length and width of the high-ohmic conductors *4* of the composite central resonator are 17.9 and 0.6 mm, respectively, and the length and width of low-ohmic pads is 2 mm. The gaps between conductors *4* and the adjacent conductors *5* are 0.1 mm wide. The working temperature of the device was determined by cooling with liquid nitrogen.

As can be seen from Fig. 2, the results of numerical simulations using a three-dimensional model of the proposed device (solid and dashed curves) qualitatively agree with the experimental data (points). A model of the HTSC film in the superconducting state used a surface resistance calculated for the working frequency [12], while the normal state was characterized by a measured resistance of 95 Ω/□ (for 0.1-μm-thick film). The terminal pads of the dumbbell shaped HTSC element had dimensions 2 × 2 mm, while the "neck" was 1.4 mm long and 0.3 mm wide. Experimental data (open circles) showed that the transmission band width (determining the working band) was about 350 MHz with a central frequency at ~2 GHz, but when the HTSC element passed to the normal state, the transmission coefficient dropped by more than 20 dB (black circles) in good agreement with the results of numerical calculations.

Figure 3a shows the power transmission characteristics of the prototype device for three values of the HTSC element "neck" width: 0.6 mm (curve *1*), 0.3 mm (curve *2*), and 0.1 mm (curve *3*). The measurements were performed in a continuous regime at a frequency of 2 GHz. As expected, there is a decrease in the threshold of power limitation with reduced width of the HTSC element "neck," which is related to an increase in the density of the high-frequency current. This is consistent with a significant difference in slopes of the curves at the initial stage (see the inset to Fig. 3a). The character of the observed behavior is related to the fact that the HTSC material used in this work belongs to type II superconductors, in which the magnetic-field-or current-induced phase transition proceeds in a certain interval rather than in a jumplike manner. As the signal power attains a threshold power, there is a coexistence of the superconducting and normal phases in this interval, the fraction of the normal phase increasing with the excess signal power. This leads to a gradual increase in the resistance of the HTSC element "neck," which is manifested by the fact that the output power of the "closed" device is independent (within definite limits) of the input power.

In designing the devices of receiver protection, it is important to know how the fractional bandwidth of the given device in the "open" state (i.e., the working frequency band) and the level of protection in the "closed" state depend on the central frequency of the preset band. In order to elucidate this question, we have numerically simulated a device that was different from the aforementioned prototype only in that the HTSC element had the form of an 0.1-mm-wide strip directly connecting the conductors of the composite resonator. Figure 3b shows the dependences of the relative bandwifth in the "open" state (solid curve) and the level of protection in the "closed" state on the cen-

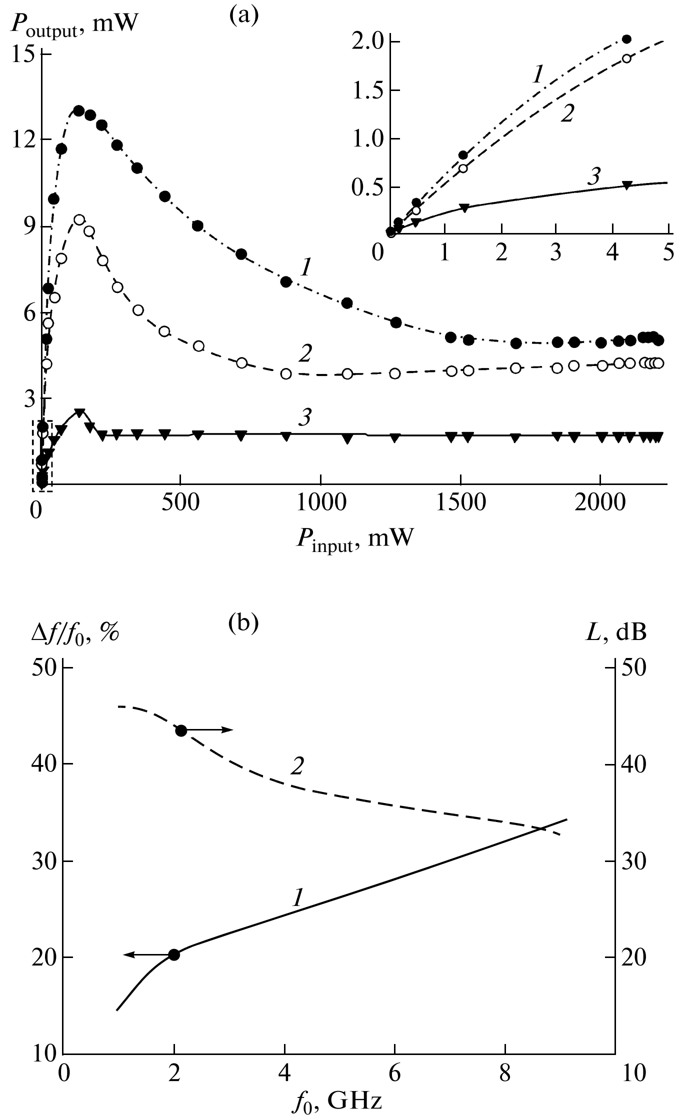

Fig. 3. (a) Experimental plots of the output power P_{output} versus input power measured for three values of the HTSC element "neck" width (mm): (*1*) 0.6; (*2*) 0.3; (*3*) 0.1. (b) Plots of the (*1*) fractional bandwidth in the "open" state and (*2*) level of protection in the "closed" state versus the central frequency for a modified device (see text for explanations).

tral frequency for this device. These results indicate that, based on the proposed design (i) it is possible to develop effective protection devices for the given frequency range and (ii) the performance of devices remains sufficiently high in a rather broad frequency range including both decimeter and centimeter wavelengths.

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