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Microwave active and nonlinear components based on high temperature superconductors (*)

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Abstract. — The microwave engineering is on the threshold of the design and manufacture of Cryogenic Microwave Integrated Circuits (CMIC) based on high-$T_c$ superconductors (HTSC), operating at the liquid nitrogen temperature. Along with HTSC delay lines, filters, and resonators, active components (modulators, switches, phase shifters) and nonlinear components (signal limiters and mixers) are considered as important constituents of CMIC'S. The problem of noise is in urgent need of being investigated. The development of computer aided design (CAD) of the microwave components mentioned above is reported. The advancement of CMIC'S is anticipated for opening up a new possibility of signal processing at microwaves.

1. Introduction.

There is widely discussed in publications and at conferences both the physical phenomena in HTSC at microwaves and the microwave applications of these materials [1, 2]. Now the efforts of researchers are shifted from investigations of the materials to design of the devices [3]. The main goal of these efforts is the realization of Cryoelectronic Microwave Integrated Circuits (CMIC'S) [4]. Higher density of microwave signals requires the improvement of the microwave system performing the signal processing at the earlier stage of the signal interceptions [5], and what can be realized on the basis of the CMIC applications. Some particular goals have been formulated in the USA like the HTSSE [6] which is seen as a basis for future development of communication satellites. Important applications of CMIC’S can be found as the basis of microwave radiometers which are used in the space borne systems of the passive microwave remote sensing of the Earth and Ocean surface. A set of the wide frequency range radiometers are being prepared for applications in Space by Russian specialists [7]. Thus the problem of the CMIC elaboration seems to be provided with a certain support.

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2. S-N-transition and resistive states of superconductive films.

The essential features of the superconductive films are not only the small microwave surface resistance which provides a small loss of transmission lines and a high quality of resonators but also the S-N-transition (S-superconducting, N-normalconducting state of the film material) which can be induced by either an ac or a dc current and exhibits itself as a large change from the film surface resistance [8]. The S-N-transition is used for the performing of microwave active elements. In this case the S-N transition is induced by a dc transport current passing through the film. This case is schematically described figure 1 presenting two values of the surface resistance of the film $R_{\text{sur}}$ on the temperature dependence $R_{\text{sur}}(T)$ at operating temperature $T_0 \approx T_c$ and at $T$ a little bit higher than $T_c$ (Fig. 1a) and a change of $R_{\text{sur}}$ between corresponding levels caused by the bias dc current $I_B$ at $T = T_0$ on the dependence $R_{\text{sur}}(I_B)$ (Fig. 1b). In the figures $T_c$ and $I_c$ are the critical temperature and current of the film. S-N-transition induced by the microwave current can be used as a basis for a signal limiter.

Experimental and theoretical investigation of the nonlinear response of high-$T_c$ superconductive transmission lines (STL) caused by a higher than usual microwave current is a very important point whether it is an unwanted or wanted manifestation or not for line behaviour. In the former case, nonlinear response indicates the upper limit at which microwave elements based on STL remain in linear operation (interconnections, delay lines, resonators, filters, antennas etc.). The latter case is the operating principle of a class of nonlinear elements (mixers, signal limiters etc.).

![Sketchy description of the S-N transition induced by dc current. Dependencies of the surface resistance on the temperature (a) and on the bias current (b).](image)

First of all, the so-called «slow» and «fast» nonlinear responses of STL should be distinguished [9]. The «slow» response can be identified as a heating effect originating from the growth of «hot spots» or normalconducting domains and exemplified by characteristic time longer than $10^{-3}$ s. The origin of the «fast» response is the kinetic processes in the electron subsystem of the superconductive films. Characteristic time of such processes is determined by an energy relaxation time $\tau_E$ which for high-$T_c$ superconductors is $\approx 10^{-11} - 10^{-12}$ s [10]. The «slow» nonlinear response of the STL limits the efficiency of the frequency conversion and should be avoided [9].

Secondly, by taking into account current density distribution across the strip conductor of STL, the edges of the strip can be considered as locations where processes leading to nonlinearity occur. It is believed that these locations (which can occupy the whole length of the
edges or can become localized at edge defects) would propagate towards the centerline of the strip with a time determined by \( \tau_E \).

If the microwave period is approximately equal to or shorter than \( \tau_E \), the longitudinal resistive state can exist. In this case the normal state induced by the microwave current is homogeneous along the edges of the film. The normal current in the edges is supported by the electric field induced by time variations of the microwave current. The longitudinal resistive state can exist during a short time interval, but it is renewed by each half period of the microwave current. This is in general agreement with the experimental results when under the microwave pulses the microwave loss in the NbN superconductive film increased while it still exhibited zero resistance with respect to a dc current \([11]\). We named this resistive state of the film potential-less (zero voltage) one. It should be noted that in the experiment the carrier frequency of the « large » signal \( f_{LO} \) was \( 10^{10} \) Hz and for NbN \( \tau_E \approx 3 \times 10^{-10} \) s so that the condition \( f_{LO} > 1/(2 \pi \tau_E) \) was met.

If the microwave period is longer than \( \tau_E \), the homogeneous distribution of the normal state along the transmission line is impossible. In this case the current is pinched into the middle part of the line resulting in the restoration of the superconductive state at the outer parts of the line. Such a situation is a nonequilibrium one, so that the normal state becomes inhomogeneous along the line, to form the transverse resistive state. For \( f_{LO} < 1/(2 \pi \tau_E) \), the alternation of superconductive and resistive sections leads to practically frequency independent extra resistance per unit length of STL. It was observed for Y-Ba-Cu-O film within the frequency range of « small » signal \( f_s = 10^5 - 3 \times 10^9 \) Hz \([9]\).

Figure 2 shows schematic diagrams of the dependencies \( R_1(f_s, I_{LO}) \), where \( R_1 \) is the resistance per unit length of the STL and \( I_{LO} \) is the amplitude of a « large » signal microwave current, for both cases described above (\( f_{LO} > 1/(2 \pi \tau_E) \)) (Fig. 2a) and \( f_{LO} < 1/(2 \pi \tau_E) \) (Fig. 2b).

S-N-transition and resistive states in a superconductive film serve as a basis for the realization of a set of microwave components of the CMIC’s. From the viewpoint of the physics of superconductivity, the phenomena mentioned form a wide field of investigation of relaxation processes and nonequilibrium noises in superconductive films.

![Schematic Diagram](image)

Fig. 2. — Qualitative dependencies of the resistance per unit length of the STL on the « small » signal frequency and the « large » microwave current for: \( f_{LO} > 1/(2 \pi \tau_E) \) (a) and \( f_{LO} < 1/(2 \pi \tau_E) \) (b) (\( \tau_E \) is energy relaxation time).

3. Active components in microwave circuits based on HTSC films.

As we have defined, the active microwave components are modulators, switches, phase shifters, and other microwave elements being linear circuits with circuit parameters which can
be changed under the influence of the dc control current [8]. The basis of active components is the S-N-transition in the superconducting film. Several examples of the active components can be presented:

1) a modulator in the form of a coplanar line [8, 9];
2) a reflective stripline switch [12];
3) a fast nonlinear switch for noise discrimination in digital circuits [13];
4) a X-shape microstrip line filter-commutator [2, 14];
5) a digital phase shifter [15, 16].

1) A microwave modulator in the form of a YBaCuO coplanar line section has been reported [8, 9]. The S-N transition in the center conductor of the line can be controlled by current video pulses [8] or by microwave pulses [9]. Figure 3 schematically illustrates the dependence of the attenuation $L = 20 \log \left( \frac{P_{in}}{P_{out}} \right)$ ($P_{in}$ and $P_{out}$ are the input and the output power of the controlled microwave signal) on the controlling current. Usual magnitudes of the attenuations in the frequency range 0-8 GHz are $L_s \approx 0.2$ dB and $L_N \approx 25$ dB for the typical dimensions of the narrow part of the line (some millimeters by 10-50 $\mu$m by 200-300-nm). For very short control pulses (some ns) switch-off and switch-on times were less than 25 ps [9].

![Schematic dependence of the attenuation of the coplanar line modulator on the bias current.](image)

2) A microwave switch made from Ti-Ca-Ba-Cu-O has been developed based on a small (100 $\mu$m by 10 $\mu$m by 50 nm) bridge, embedded in a 50 Ohm coplanar transmission line, driven in the normal state normal via a current in an external control line made from Ti-Au, which provides heating and magnetic fields for switching and was separated from the bridge by a thin dielectric [12]. In the on-state, the insertion loss was less than 1 dB over the range of 0.5-8.5 GHz. Isolation in the off-state exceeded 30 dB. Response times were on the order of a microsecond (switch-off time was about 1 $\mu$s and switch-on time about 5 $\mu$s) due to heat storage in the surroundings while the bridge was being heated.

3) Measurements of fast nonlinear switching of Y-Ba-Cu-O film, in the form of a small bridge (200 $\mu$m by 25 $\mu$m by 100 nm), between the dissipative state induced by an electrical current, and the superconducting state have been reported [13]. System rise and fall times were measured to be about 1 ns. A novel scheme for noise discrimination in digital circuits using this switching has been proposed and experimentally demonstrated for speeds exceeding 200 Mb/s. In this scheme the signal circuit was shunted by the bridge with dc bias current. At the low signal level the noise had completely disappeared because the noise current through the bridge was below critical current. At the high signal level, the bridge switched to the dissipative state with relatively high resistance, resulting in a transmission through the signal circuit.

4) The X-shape microstrip line filter-commutator, suggested in [2, 14]. It is schematically described in figure 4 along with the equivalent circuit of one of the four symmetric channels.
Any channel can be connected with one of three other channels, while two remainder channels are disconnected. Commutation of the channels are performed by S-N transition in pairs of key elements (narrow meander inductive elements) in the disconnected channels. The synthesis of the filter-commutator has been carried out for the case of the center frequency 10 GHz and for the relative passband of the filter 0.2. The calculated frequency dependence of the insertion loss of two connected channels (while two other channels were disconnected by key-elements being in the N-state with isolation at about 30 dB each) had a Chebyshev band-pass characteristic with maximum insertion loss of about 0.1 dB for the values of the surface resistance in S- and N-states exhibited in figure 1, and for particular geometry of the key-elements.

5) Two possible versions of a high-$T_c$ superconductor phase shifter have been reported [15, 16]. The main difference between them is the design. One design is a realization of a hybrid microwave circuit which has passive networks that are made of YBaCuO film and the switching elements are $\rho$-i-n-diodes [15]. According to the authors [15] it is possible to use relatively narrow strip lines, required for optimum design, without an essential increase of the insertion loss. Another solution seems to have considerable promise [16]. In this version, current controlled YBaCuO film switches in the form of a narrow meander line section (similar to that in the filter-commutator [2, 14]) which are used as switching elements instead of the $\rho$-i-n-diodes. A 180°-phase shifter layout is shown in figure 5. The insertion loss is 1-1.5 dB in a 10 % bandwidth around the central frequency 5 GHz. The phase shift is accurate if not to better than 10 %.

Two characteristics of the superconductive films used as a basis of active components are important:
Fig. 5. — Layout of the 180° phase shifter.

— the commutation quality of the film;
— the duration of the S-N-transition.

The commutation quality $q$ is the ratio of surface resistance in N- and S-states of the film [2]:

$$q = \frac{R_{\text{sur}}^{(N)}}{R_{\text{sur}}^{(S)}}.$$  

The $q$-type parameter is quite universal and well-known in the microwave switch theory [17]. For the superconductive film the $q$-parameter can be presented as [2]:

$$q = \begin{cases} \frac{1}{4} (\delta_{sk}/\lambda_L)^4, & h \ll 2 \lambda_L \ll \delta_{sk} \\ \frac{1}{2} (\delta_{sk}/\lambda_L)^3, & 2 \lambda_L \ll \delta_{sk} \ll h \end{cases}$$

where $\delta_{sk}$ is the skin-depth for the film material in the N-state and $\lambda_L$ is the magnetic penetration depth in the S-state. Figure 6 illustrates the distinctive dependence of $q$-parameter on the film thickness.

Fig. 6. — Distinctive dependence of $q$-parameter ($q = \frac{R_{\text{sur}}^{(N)}}{R_{\text{sur}}^{(S)}}$) on the film thickness.
on the film thickness \( h \). The notations used are the following:

\[
q_s = \frac{1}{2} \left( \frac{\delta_{sh}^2}{\lambda_L} \right)^3, \quad q_s = \frac{1}{4} \left( \frac{\delta_{sh}^2}{\lambda_L} \right)^4
\]

The appropriate characteristics of the component mentioned above can be realized if the film has \( q \approx 10^3 \). For the HTSC films this condition can be obtained up to 50 GHz. It is worth mentioning that for a designer of signal limiters and microwave switches a high value of \( q \)-parameter can turn out to be more desirable than the extremely small value of the surface resistance of the film being in the superconductive state.

The duration of the S-N-transition is determined by both the kinetic progresses in the superconductor and the thermal processes mainly in the substrate region adjoined to the film [9, 18]. The duration of the leading front of the commutation pulse (S \( \Rightarrow \) N-switching) is determined by the kinetic processes and can be estimated as \( 10^{-11} \) s [9]. The duration of the trailing front (N \( \Rightarrow \) S-relaxation) is determined by the process of the film cooling and depends on the thermal conductivity of the substrate. For sapphire substrate at \( T = 77 \) K the cooling relaxation time is about \( 10^{-7} \) s [18].

4. Signal limiters in microwave circuits based on HTSC films.

Signal limiters are based on the S-N-transition induced by the microwave signal. Such microwave components can be used for a protection of the front-end of the microwave receivers. The HTSC signal limiter which was first reported about, had been performed as a HTSC stripline section [8] and a stripline resonant structure [14]. A coplanar line version of the signal limiter has been described as well [2, 9].

A signal limiter in the form of a waveguide filter has been investigated [19]. The limiter was implemented as a two-element filter comprising of the resonant diaphragms made of copper foil and spaced by a quarter-wave piece of an X-band waveguide. The cross strips made of YBa\(_2\)Cu\(_3\)O\(_{7-x}\) films are put in the center of the diaphragms. Figure 7a shows the scheme of an experiment with the power limiter, while figure 7b shows the configuration of YBa\(_2\)Cu\(_3\)O\(_{7-x}\) key-elements. When the key-element is in the normal conducting state, the \( Q \)-factor of the diaphragm decreases to a great extent and the resonance frequency of the diaphragm decreases as well. As a result the amplitude-frequency characteristic of the limiter changes depending on the microwave power level. For the low level of microwave signal, a Chebyshev band-pass filter characteristic with \( f_0 = 10 \) GHz, \( \Delta f/f_0 = 0.1 \), and the maximum insertion loss less than

![Fig. 7. X-Band waveguide power limiter (a) and the configuration of the key-elements (b).](image-url)
0.5 dB is obtained. A frequency independent isolation about 25 dB is obtained if the microwave signal level is higher than a certain critical value.

If S-N transition is initiated by an external biasing current passing through the superconducting strips, then the waveguide filter in the form of two resonant diaphragms loaded by the superconductive strips can also be used as a microwave switch. Such devices have been fabricated for the frequency ranges of 65 GHz and 145 GHz on the basis of NbN film for operational temperature 5 ± 7 K [20]. The insertion losses are less than 0.5 dB at 65 GHz and less than 1 dB at 145 GHz within a 5-10% bandwidth. The feature of these devices is that both diaphragms and strips were made of the same NbN film, which allows the increase of the resonator quality factor. Furthermore, it is obvious that the S-N transition can be caused by a microwave signal being in excess over the threshold level.

The most important characteristic of the microwave signal limiter is the time duration of the response of the limiter to the incident wave. The first experiments with the nonlinear fast response of the HTSC transmission lines show that the time of the HTSC film response at \( T = 77 \text{ K} \) is less than \( 10^{-11} \text{ s} \) [9].

A millimeter wave (37 GHz) filter-limiter based on the nonsymmetrical fin-line in a waveguide has been reported [21]. Two YBaCuO film key-elements (30 \( \mu \text{m} \) width) short out the ends of the \( \lambda/4 \)-slot stubs spaced also at \( \lambda/4 \) interval (Fig. 8). For the S-state of the key-elements insertion loss was less than 0.2 dB and for the N-state 18 dB in 10% bandwidth. Measured switch-off time was less than 0.2 ns and limited by the set-up accuracy.

![Figure 8](image)

Fig. 8. — Millimeter wavelength filter-limiter (a) and the method of key-element insertion (b).

5. Frequency mixers based on HTSC films.

There are many publications concerning the investigations of the nonlinear phenomena in the superconductors which are directed to provide frequency mixing. Experiments on frequency mixing can be classified under two types:

1) short film bridge frequency mixers [22-27];
2) frequency mixers based on the nonlinear superconductive transmission lines [4, 9].

Short bridge frequency mixers reported [22-26], are based on the nonlinearity of the grain-boundary weak links [22-25] in granular high-\( T_c \) thin films, or on the nonlinearity of the Josephson junction specially manufactured within the bridge by means of the step-edge techniques [26]. The Josephson junction mixers provide quite low noise and a wide frequency band in the microwave and millimeter wavelength region. However only a small dynamic range can be obtained with them.

The short film bridge mixer or the nonlinear transmission line mixer can be based on the nonlinearity of the resistive state of the superconductive film (see part 2). Some results of experimental investigation of the frequency conversion in HTSC coplanar line have been
reported [9]. The coplanar line section serving as a mixer was manufactured using ion-beam etching from dc-sputtered Y$_1$Ba$_2$Cu$_3$O$_{7-x}$ film on MgO substrate. The critical temperature of the film was $T_c = 89$ K, the surface resistance at $f = 87$ GHz and $T = 77$ K, $R_{\text{surf}} \equiv 10^{-2}$ Ohm. The length of the narrow inner conductor part of the line was $L = 4$ mm, width $w = 10 \mu$m, and characteristic impedance $\rho = 50$ Ohm.

The coplanar line section is excited simultaneously by two CW-signals: «large» or local oscillator (LO) signal ($f_{\text{LO}} = 1.5$ GHz) and «small» signal ($f_s = 2$ GHz). In this case the section with respect to the «small» signal represents a linear but time-varying system. The time variations of the system parameter (or parameters) are originated by the LO signal. As a result conversion to the intermediate frequency ($f_1 = 2 f_{\text{LO}} - f_s = 1$ GHz) occurs.

At the top of figure 9 dependencies of the attenuation of «small» signal caused by LO on the LO-power are shown for different temperatures ($T = 88$ K-curve 1, $T = 87$ K-curve 2, 

![Graph](image-url)

Fig. 9. — Dependencies of the attenuation of the «small» signal, conversion loss and input effective noise temperature of the coplanar line mixer on the LO-power for different temperatures.
The estimation of noise properties of the coplanar line mixer can be obtained from measurement of effective input noise temperature $T_c$ of the superconductive transmission line influenced by LO-power. In the experiment $T_c$ was measured as a function of LO-power within frequency range 0.1-1.6 GHz while the coplanar line section was excited by LO with frequency 5 GHz. The results are shown at the bottom of figure 9. The dotted line in the graph corresponds to the uncertainty level of the measurement set-up (about 20 K).

A conclusive option of the mixer design will be done after making a lot of mixer design versions and a comparison with practical results. It is believed that the mixer based on the nonlinear coplanar line is a quite promising version for applications as a component of the CMIC.

The question could be raised about the benefits which could be provided by the development of the new type of superconductor mixers in comparison with the well-known semiconductor microwave and millimeter wavelength mixers. Indeed, state-of-the-art performance has been recently achieved at millimeter wave length with an active mixer fabricated using InP HEMT devices [27]. The favourable combination of low noise, large dynamic range and high critical frequency can be anticipated for a microwave receiver based on such a HEMT mixer. The advantage of the HTSC coplanar line mixers, being correlated with HEMT mixers on characteristics enumerated above, is the homogeneity of the fabrication process. HTSC mixers can be produced from the same film as other elements of the CMIC’s.

Figure 10 illustrates the estimation of the noise level and dynamic range of the mixer based on the nonlinear coplanar line in comparison with the S-I-S mixer.

![Diagram](image_url)

**Fig. 10.** Estimation of the dynamic range of the coplanar line mixer in comparison with the S-I-S mixer.
6. On the nature of noises of switched superconducting film.

Two kinds of noises in the superconductive mixer should be considered-equilibrium and nonequilibrium ones. The nonequilibrium (or extra) noise arises under the influence of the kinetic processes in the material. The extra noise can be caused by the transport current or the microwave pumping. Several channels of conversion of the pumping energy into nonequilibrium noise can be proposed:

1) the Josephson-like generation of the weak links between crystal blocks or twinning domains [28];
2) the formation, motion, or/and recombination of magnetic vortices [29];
3) the heating of the electron subsystem of the film away from the crystal lattice [10].

There is no reliable experimental measurements of microwave noise in a superconductor film influenced by a transport dc current or a microwave pump. One can pay attention to the noise measurement in the short bridge millimeter wavelength mixer [23] which exhibited the moderate level of the noise.

The following source of the noise in the resistive state of the superconductive film connected with the birth of Phase Slip Lines (PSL) is worth discussing. Sometimes the PSL’s are treated as « hot spots » generated by a current higher than the critical one. They have been observed experimentally in both conventional superconductors [30] and HTSC [31]. The birth of PSL’s is accompanied by the voltage drop jumps which emit electromagnetic radiation. Since the time constant of the PSL formation is about $\tau_E$, the noise spectrum should be homogeneous up to the frequency of about 1 GHz for HTSC.

7. Development of CAD for the CMIC’s.

The design of the CMIC’s requires the CAD provision. The CAD of the CMIC’s can be presented as:

1) modelling the HTSC film surface resistance;
2) modelling of the current density distribution across the thin superconductive film and taking into account therein the computation of the transmission line parameters;
3) modelling the lumped elements of the CMIC’s in S- and N-states;
4) modelling the nonlinear processes in HTSC bridges and transmission lines;
5) modelling the time-depended processes of the S-N-transition.

The first three parts of CAD are now in progress.

A simple theoretical description of the high-$T_c$ superconductor properties can be made on the basis of the bipolaron Bose-condensation model [32]. This model was used for developing formulae of the surface resistance $R_{\text{surf}}$ of the high-$T_c$ bulk samples and thin films [33-35]. The disputable point of the model presentation is the dependence of the London penetration depth on the temperature:

$$\lambda_L^{-2}(T) = \lambda_L^{-2}(0) \cdot [1 - (T/T_c)^\gamma].$$

The canonical empirical law for classical BCS-like superconductors gives $\gamma = 4$. The simplest Bose-condensation model leads to $\gamma = 3/2$ [32]. Some recent, more or less reliable experimental results [36-38] make it possible to accept $\gamma = 2$. Generalized analysis of the experimental data on temperature and frequency dependence of $R_{\text{surf}}$ [39] shows the value of $\gamma = 3/2$ is quite suitable for the quantititative description of the $R_{\text{surf}}$ as a function of the temperature. The residual resistance should be taken into account as well [34, 35]. Some theoretical considerations [37, 38] draw a conclusion that $\gamma = 2$ can be generally accepted in a wide temperature region.
Itoh used the presentation of $R_{\text{sur}}$ with $\gamma = 3/2$ for the description of the short pulse propagation in the HTSC transmission line [40, 41] and obtained a good agreement between calculated and measured data.

Thus the following formula can be used for the numerical description of $R$ of a bulk HTSC sample:

$$ R_{\text{sur}} = \frac{1}{2} (\omega \mu_0)^2 \cdot \lambda_{1}(0) \cdot \sigma_N(1) \frac{t^{3/2} + \alpha (1 - t^{1/2})}{(1 - t^{3/2})^{3/2}}, \quad \text{for} \quad t = T/T_c < 1. $$

The model parameters:

$T_c$ is the phase transition temperature, $\lambda_{1}(0)$ is the penetration depth at $T = 0$, $\sigma_N(1)$ is the conductivity at $T = T_c$, $\alpha$ is the measure of the residual resistance.

Typical values for YBa$_2$Cu$_3$O$_7$ are $T_c = 90$ K, $\lambda_{1}(0) = 0.2$ $\mu$m, $\sigma_N(1) = 10^6$ (Ohm.m)$^{-1}$, $\alpha = 0.8$.

Thickness of the films should be taken into account [see for example 2, 4]. By taking into account the current distribution one can obtain the simple formula for the resistance per unit length of the microstrip line [42]:

$$ R_1 = \frac{R_{\text{sur}}^{(\text{trg})}}{w} \frac{8}{\pi^2} \left[ 1 + \frac{1}{4} \ln \left( \frac{w}{\lambda_{\perp}} - 1 \right) \right] + \frac{R_{\text{sur}}^{(g,p)}}{w} \frac{w}{2 \pi h}, \quad \text{for} \quad w \equiv h $$

where $\lambda_{\perp} = \frac{2 d^2}{\lambda_L}$, $R_{\text{sur}}^{(\text{trg})}$ and $R_{\text{sur}}^{(g,p)}$ are surface resistance of the film strip and the ground plane of the microstrip line.

Among the lumped elements of the HTSC microwave integrated circuits, the meander line structures should be paid attention to. The structures are used as S-N-transition switches being almost inductance in S-state and a pure active resistor in the N-state. Experimental measurements of the meander line structures were made [9] and suitable numerical presentations have been found.

All of that is used for developing the HTSC microwave CAD which has been applied to design of several structures [14, 16]. The software oriented to an ordinary user will be accomplished in the immediate future.

The CAD blocks concerning nonlinear and time dependent processes are now seen to be very important and will be urgently worked out.

8. Conclusion.

The active and nonlinear components based on HTSC along with HTSC delay lines, filters, and resonators make up a set of components which can lead to the design and manufacture of the CMIC’s and, hence, form the new branch in the progress of microwave electronics. Many problems of the microwave signal processing can be solved in the framework of the components described. In this respect the set is complete. All components of the complete set are based on the similar physical phenomena and can be realized on the superconductive films. This provides the homogeneity of the CMIC production technology.

For the future development of the CMIC’s, the voltage tunable microwave generator can be imagined. The basis of such a generator could be an array of the Josephson junctions which consists of several thousands junctions performed on the HTSC thin film. Such a design can be inserted in the homogeneous production technology of the CMIC’s based on the thin HTSC films.
One can find in publications the description of a microwave transistor based on the thin HTSC film and the set of Josephson junction [43-45]. But it is difficult to predict the successful progress of amplifier with the low noise and the large dynamic range based on such a transistors. The question about the microwave transistor based on HTSC film is still open.

References


*Proof not corrected by the authors.*