The Use of Coplanar Transmission Lines for Protecting Receiving Antenna Systems from Powerful Electromagnetic Radiation in a Wide Frequency Range

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Abstract. The goal of the work is to expand the frequency range of operation of coplanar waveguide transmission lines as broadband high-speed superconducting protection devices against powerful ultrashort electromagnetic radiation, and to apply them in antenna devices of radio electronic systems designed to ensure the reliable operation of critical infrastructure facilities. The aim is achieved by solving the following tasks: investigating the electrophysical properties of coplanar transmission lines, in particular, capacitance, surface and wave resistance in different phase states that arise under the influence of powerful electromagnetic radiation, and determining the main factors for effective protection in a wide frequency range, designing protective devices. The most important result is the establishment of the possibility of using coplanar transmission lines as protection devices in a wide frequency range up to 100 GHz, as well as the establishment of the dependence of their main characteristics on the design parameters of the superconducting protection device. The significance of the obtained results consists of solving a complex problem of providing protection of antenna systems against powerful ultrashort radiation by establishing an analytical relationship between the electrophysical parameters of coplanar waveguide transmission lines, which are in different phase states determined by the influence of powerful electromagnetic radiation, and their design parameters. The peculiarity of the obtained results is in the clarification of the dependence of the wave resistance of the coplanar waveguide transmission lines in superconducting, mixed, and normal phase states on the change of their active component of surface resistance, determined in turn by the design characteristics of the protective device. The difference from the known works lies in obtaining relationships for determining the wave resistance of protective devices in different phase states.
Keywords**:** critical infrastructure facilities, antenna system, pulsed high-power ultrashort-duration electromagnetic radiation, protective device, coplanar strip transmission line.

DOI: doi.org/10.52254/1857-0070.2023.1-57.11
UDC: 621.396.677

Studiul utilizării liniilor de transmisie coplanare pentru protecția sistemelor de antene receptoare de radiații electromagnetice puternice într-un diapazon larg de frecvențe

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Rezumat. Scopul lucrării este extinderea diapazonului frecvențelor de funcționare a liniilor de transmisie coplanare stripline, ca dispozitive de protecție repide cu bandă largă și supraconductoare împotriva radiațiilor electromagnetice de mare putere de durată ultrascurtă şi folosite în antenelw sistemelorn radio-electronice utilizate,

destinate pentru a asigura funcționarea fiabilă în primul rând a obiectelor infrastructurii critice, precum centrale nucleare și termice, rafinării de petrol și gaze, terminale petroliere, aeroporturi, depozite de produse finite, arsenale militare. Acest obiectiv este atins prin rezolvarea următoarelor probleme: studierea proprietăților electrofizice ale unei linii de transmisie coplanare, în special, capacitatea, rezistența la suprafață și a undei în diferite stări de fază care apar sub influența radiațiilor electromagnetice puternice și determinarea principalelor factori pentru asigurarea unei protecții eficiente într-o gamă largă de frecvențe, proiectarea dispozitivelor de protecție. Cel mai important rezultat este stabilirea posibilității utilizării unei linii de transmisie coplanare ca dispozitive de protecție într-o gamă largă de frecvențe de până la 100 GHz, precum și stabilirea dependenței principalelor sale caracteristici de parametrii constructivi ai unui dispozitiv de protecție supraconductor. Semnificația rezultatelor obținute constă în rezolvarea problemei complexe a asigurării protecției sistemelor de antene împotriva radiațiilor de mare putere de durată ultrascurtă pe baza stabilirii unei relații analitice între parametrii electrofizici ai liniilor de transmisie coplanare stripline în diferite stări de fază, determinate prin impactul radiațiilor electromagnetice de mare putere și al parametrilor constructivi. Particularitatea rezultatelor obținute este precizarea dependenței de rezistență a undelor a liniilor de transmisie, a liniilor de bandă coplanare în stările de fază supraconductoare, mixtă și normală de modificarea componentei lor active a rezistenței de suprafață, care la rândul său este determinată de proiectare caracteristicile dispozitivului de protecție. Diferența față de lucrările binecunoscute este de a obține să se determine rezistența la undă a dispozitivelor de protecție în diferite stări de fază.

Cuvinte-cheie: obiecte de infrastructură critică, radiație electromagnetice pulsate de mare putere de durată ultrascurtă, sistem de antenă, dispozitiv de protecție, linie de transmisie coplanară stripline.

Применение компланарных линий передач для защиты приемных антенных систем от мощного электромагнитного излучения в широком частотном диапазоне

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Аннотация. Целью работы является расширение частотного диапазона функционирования компланарных полосковых линий передачи, как широкополосных быстродействующих сверхпроводящих устройств защиты от мощного электромагнитного излучения ультракороткой длительности, и применяемых в антенных устройствах радиоэлектронных систем, предназначенных для обеспечения надежного функционирования объектов критической инфраструктуры, прежде всего, таких как атомные и тепловые электростанции, нефтегазоперерабатывающие предприятия, нефтяные терминалы, аэропорты, склады готовой продукции, воинские арсеналы. Поставленная цель достигается за счет решения следующих задач: исследования электрофизических свойств компланарной линии передач, в частности, емкости, поверхностного и волнового сопротивлений в различных фазовых состояниях, возникающих под воздействием мощного электромагнитного излучения и определения основных факторов обеспечения эффективной защиты в широком частотном диапазоне, конструктивной разработки устройства защиты. Наиболее важным результатом является установление возможности применения компланарной линии передачи в качестве устройств защиты в широком частотном диапазоне до 100 ГГц, а также установление зависимости ее основных характеристик от конструктивных параметров сверхпроводящего устройства защиты. Значимость полученных результатов состоит в решении сложной задачи обеспечения защиты антенных систем от мощного излучения ультракороткой длительности на основе установлении аналитической связи между электрофизическим параметрами компланарных полосковых линий передачи, находящихся в разных фазовых состояниях, определяемых воздействием мощного электромагнитного излучения, и их конструктивными параметрами. Особенность полученных результатов заключается в уточнении зависимости волнового сопротивления компланарных полосковых линий передачи в сверхпроводящем, смешанном и нормальном фазовых состояниях от изменения их активной составляющей поверхностного сопротивления, определяемой в свою очередь конструктивными характеристиками устройства защиты. Отличие от известных работ заключается в получении соотношений для определения волнового сопротивления устройств защиты в разных фазовых состояниях. Практическое применение устройств защиты на основе компланарных полосковых линий передачи существенно повысит надежность функционирования антенных систем в условиях воздействия мощного электромагнитного излучения ультракороткой длительности.

Ключевые слова: объекты критической инфраструктуры, импульсное мощное электромагнитное излучение ультракороткой длительности, антенная система, устройство защиты, компланарная полосковая линия передачи.

INRODUCTION

The problem of ensuring the reliability of critical infrastructure has always been in the focus of researchers. Currently, given the expansion of combat zones and the increasing level of terrorist threat, the need to solve this problem is becoming increasingly important. Among the many factors that could affect critical infrastructure, one of the central places is occupied by the impact of powerful electromagnetic pulse radiation on electronic equipment that is part of the complex of means for protecting and securing these objects. Electronic equipment has always been an integral part of the security system for critical infrastructure objects such as nuclear and thermal power plants, oil terminals, oil and gas processing plants, airports, warehouses, and military arsenals.

The most dangerous impact on the electronic equipment of means for protecting and securing critical infrastructure objects is the electromagnetic pulse of ultrashort duration. Due to its small duration, it has high penetrating ability and a specific reaction of electronic equipment to such an impact. The electromagnetic pulse can spread to sensitive elements of electronic equipment both through the antenna-feeder path and through structural elements (panels, windows, unshielded conductors, etc.).

To ensure the reliability of the functioning of radio-electronic means of security and safety of critical infrastructure objects under the influence of powerful electromagnetic radiation, which includes antenna systems, it is proposed to use high-speed protective devices based on high-temperature superconductors (HTSC) [1, 2]. For example, in [3], microstrip transmission lines (MST) are proposed for the protection of the antenna systems of radio-electronic means against the effects of powerful electromagnetic radiation. However, the operating frequency range of such devices is limited to about 100 MHz with limited design parameters, which is a significant disadvantage, since the bandwidth of pulse radiation can reach much larger values, up to 10^{18} Hz. Therefore, there is a need to search for more effective ways to protect radio-electronic means that have better frequency characteristics within the limitations of the design parameters of the protection means.

In works [4, 5], to create ultra-high frequency devices, particularly filters operating at frequencies up to 350 GHz and waveguides at frequencies up to 220 GHz, it is proposed to use coplanar transmission lines (CPL), which indicates the potential for a significant expansion of the operating frequency range of protective devices using such transmission lines. This circumstance suggests the expediency of conducting research aimed at determining the possibility of using coplanar transmission lines to create fast-acting protection devices for antenna systems of radio electronic security means and ensuring the safety of critical infrastructure objects operating in a much wider frequency range.

Literature analysis

In [1], a methodology for studying the parameters of microstrip transmission lines, including the determination of the surface impedance, is presented. However, the method for finding the desired parameters is carried out without taking into account the parameters of the electromagnetic radiation (EMI) affecting the thin-film transmission line.

In [2], a study of transient processes in a superconducting protective device is carried out. The possibility of the occurrence of undamped oscillations and their impact on the operation of radio-electronic equipment is evaluated. However, the authors did not pay attention to determining the influence of powerful EMI on the transient processes, taking into account the pulse duration.

In [3], the results of substantiating the approach to describing the response of an arbitrary antenna to the impact of EMI are presented. Analytical relationships are given for assessing the influence of radiation on a superconducting protective device located in superconducting, mixed, and normal phase states.

In [4], a procedure for the partial inversion of the Cauchy singular integral and the integral with a logarithmic singularity, defined on a finite set of bounded intervals, is presented. Based on this, an electromagnetic model of a shielded coplanar transmission line is constructed. Results of the calculation of spectral characteristics and distributions of the field of the structure's own waves are presented, as well as data on the convergence of the approximate solution.

In work [5], the possibility of using a flat section of a high-temperature superconductor-based radio frequency line as a protection device for electronic systems against pulsed electromagnetic signals is considered. The results of experimental studies of the behavior of a thin-film coplanar section of the line (YBa2Cu3O7-x on sapphire) under the influence of pulsed radiation of varying power and duration are presented. It was established that with an increase in the duration of the pulse, the superconductor transitions into a resistive state, cause leading to an increase in losses.

In [6], the nonlinear properties of a coplanar waveguide based on an epitaxial thin film of high-temperature superconductor YBa2Cu3O7-δ, deposited on a single-crystal substrate of Al_2O_3, are investigated in the X-band and temperature range from 77K to 90K. It is shown that the application of a DC bias to the structure allows for control of the microwave nonlinearity of the transmission line. Periodic features of losses depending on temperature indicate that the phase constant of the propagation has nonlinear behavior associated with the properties of the transmission line. The phenomenological characteristic power value P_0 is determined by comparing experimental data with the results of theoretical analysis. However, the authors did not pay attention to the issues of estimating spectral characteristics.

In work [7], the results of studying a 40 GHz radio frequency biosensor using a microstrip transmission line for the dielectric characterization of cancer cells are presented. It is suggested to use a classical coplanar waveguide to ensure a passband of up to 40 GHz for the biosensor.

In [8], a universal method for analyzing arbitrary planar layered transmission lines is proposed, and its features are considered. The stages of implementing the method for analyzing the parameters of planar layered transmission lines, constructed using the Galerkin procedure in the spectral domain, are presented. The results of analyzing test planar layered structures are presented. However, the authors did not address issues related to the study of spectral characteristics of the investigated transmission lines.

In [9], the results of the development of a general transmission line model for predicting the frequency-dependent response of compact modulators are presented. The calculation of the radio frequency parameters of the modulators is carried out taking into account the dimensions of the coplanar waveguide. The accuracy of the model in predicting the 3 dB modulation bandwidth of the devices is evaluated by comparison with experimental results. Recommendations are given for designing devices with significantly improved achievable modulation bandwidth, which are presented through the optimization of radio frequency and optical parameters. The modulation bandwidth was 100 GHz. It is claimed that the presented model is applicable to any type of super-compact electro-optic modulators.

In [10], the results of studies on symmetrical coplanar transmission lines with end coupling (SCTL) are presented. Attention is given to the question of organizing turns in the SCTL. A regular section of a matched line with strictly anti-phase wave excitation in it implies electrical symmetry of currents in conductors with respect to the longitudinal axis of the line. As a result of the conducted studies, it was established that the proposed turn option provides practically the same energy characteristics of the SCTL as the regular section of the same length. Other issues were not studied, in particular those related to the evaluation of spectral characteristics.

In [11], an overview of the main results obtained by the authors in the process of studying non-traditional superconductors and developing microwave devices based on cuprate high-temperature superconductors is presented. The results of studies on epitaxial films of the cuprate superconductor $YBa2Cu3O_{7-\delta}$ and Fe-containing superconductors are presented. The complex conductivity, including the fluctuation conductivity, was determined. Temperature dependencies of the complex conductivity of $YBa2Cu3O_{7-\delta}$ superconductors and the corresponding physical quantities were obtained, which allows one to judge about the relevant scenarios of wave symmetry in the gap function of the studied superconductors. The possibility of creating large-scale devices based on high-temperature superconductors operating at frequencies up to 40 GHz was experimentally established. However, the issues of determining wave resistances taking into account the destruction of superconductivity were not addressed in this work.

In [12], an analysis of loss characteristics affecting the series resistance of coplanar waveguide interconnects with grounding is presented. Experimental dependencies corresponding to lines with different screens are shown up to 30 GHz. The influence of geometry, in particular, the width and spacing between tracks on the series resistance of different resistive components was studied. In addition, a time-domain analysis was performed to assess the impact of neglecting each of the resistive components on the quality of a digital signal with a speed of several gigabits per second. However, issues of waveguide interaction with electromagnetic interference were not considered in this article.

In [13], the possibility of microwave glucose diagnostics in real-time without the use of labels based on the construction of a classical coplanar waveguide (CPW) is shown. The biosensor is implemented with a 50 Ohm CPW transmission line, where a 3 mm diameter localized in the center of the CPW transmission line was used for detection. The CPW transmission line is made of FR4 microwave laminate. Electromagnetic interaction was performed with a varying dielectric constant of an aqueous solution. The measurement results showed good sensitivity of 108.4 MHz/mg/ml and high accuracy with a good coefficient of linear regression of 0.997. At the same time, the electro-physical parameters of the biosensor were not provided or considered by the authors during the research.

In [14], a microwave sensor in the form of a capacitive matrix is presented for label-free detection of Escherichia coli. The results of theoretical researches were confirmed by the implementation of a sensor chip made using the United Monolithic Semiconductor (UMS) PH25 process on a 100 μm thick GaAs substrate, and measurements of various concentrations of Escherichia coli in the frequency range of 1...3 GHz. The obtained results are promising for future biomedical applications in terms of detecting specific bacteria. The authors did not conduct any other research.

In work [15], the results of studies on the dependence of the duration of the S-N phase transition on small values of the input signal voltage amplitude are presented. However, the dependence of the wave resistance of the superconducting film in different phase states under the influence of electromagnetic interference was not studied.

In [16], the results of determining the penetration depth of electromagnetic waves into a superconducting film and its surface impedance are presented. The authors provide the dependence of the quality factor of the superconducting film on its thickness. However, the authors did not pay attention to the effect of powerful electromagnetic interference on changes in the phase state of the film and the determination of the surface resistance under these conditions.

In [17], based on the conformal mapping method, an analysis of the ideal suspended coplanar waveguide model was conducted, and the wave impedance was determined. A self-assembled suspended coplanar waveguide (SCPW) was proposed and implemented using multi-layer printed circuit board technology with experimental losses of no more than 0.5 dB and return losses better than 15.8 dB from DC to 10 GHz, which eliminates the traditional disadvantages of suspended schemes, such as bulky size, high weight, and integration complexity due to their mandatory metallic cavity and mechanical assembly.

In [18], an approach to designing a filtering rat-race coupler (FRRC) with hybrid resonators with an integrated circular substrate waveguide (CSIW) and coplanar waveguide (CPW) is proposed. The FRRC is designed in a single CSIW resonator with four integrated CPW resonators and four miniature input ports. The 0 and 180 degree phase characteristics of the RRC are realized by the self-phase and anti-phase electromagnetic fields of the CSIW dual-mode resonator. By properly placing the sum, difference, and two other output ports, the FRRC is used to achieve the desired RRC properties with bandpass filter responses. In addition, transmission zeros are generated near the upper stopband. A miniature FRRC using hybrid CSIW and CPW resonators was synthesized, fabricated, and tested in a single-layer process to verify and demonstrate its advantages over previous modern research, including miniature size, high quality, high-order filter responses, and improved out-of-band signal suppression.

In [19], a dual-polarized cross-dipole antenna with a bandwidth for 2G/3G/4G base station applications is proposed using a grounded coplanar waveguide (GCPW) filter. The cross-dipole antenna with the GCPW feeding structure is designed to cover frequencies from 1.7 to 2.7 GHz. A compact GCPW filter is proposed inside the dipole antenna to provide a frequency band of 2.2...2.5 GHz. As a result, the proposed antenna has two operating bands of 1.67...2.23 GHz and 2.45...2.75 GHz for VSWR <1.5 and a sharp rejection band of 2.23...2.45 GHz. The measured isolation is above 26 dB, the half-power beamwidth is about 68°, and the average gain is around 8.3 dBi over the entire operating band. The minimum gain in the rejection band is -9 dB, which is by 17 dB lower than the gain at the operating frequency. The research questions regarding wave impedance were not studied.

In [20], an integrated terahertz range directional diagram is presented. Submillimeter single-mode coplanar waveguides with a benzocyclobutene polymer-based conductor and a ground plane transition between the planes up to 760 GHz have been processed and measured. Good agreement between analytical and numerical modeling has been experimentally demonstrated. Two-level Thru-Reflect-Line and square root of Thru de-embedding corrections are applied to extract the attenuation coefficient of about 3 dB/mm at 600 GHz, the relative phase velocity with respect to light of about 0.716, and the characteristic impedance of about 50 Ohms. It has been established that the losses of the coplanar waveguide are at the cutting-edge level, paving the way for fully integrated terahertz range circuits.

In [21], a new topology variant is presented: the folded ESIW, which is half the width of the original ESIW waveguide and maintains the same cross-sectional area with good performance and a similar bandwidth. The feasibility of the new topology is discussed. To verify and confirm this proposal, a parallel prototype was designed, fabricated, and measured, and the results were promising, opening up access to new design strategies in the field of ESIW.

In [22], two coplanar waveguide bandpass filters operating at a frequency of 350 GHz were investigated. Both filters were based on quarter-wave resonators with stepped impedance, which can be easily integrated into on-chip systems. A second-order Chebyshev filter and a fourth-order quasi-elliptic filter were jointly developed to determine the characteristics of the roll-off. Both filters were made of superconducting niobium film using optical lithography and lift-off process, which can reduce significant metallic losses in the terahertz range. It is shown that the calibrated transmission characteristics, compared with the simulation, demonstrated that such superconducting coplanar waveguide filters could be used in a future terahertz astronomical spectrometer.

In [23], a new transition between coplanar waveguide (CPW) and rectangular waveguide (RWG) filled with air is presented. A rectangular radiator with an elliptical slot is connected to the central conductor of the CPW to implement the transition, which expands the passband. This direct transition does not require an intermediate transition or air bridges. The planar transition scheme is made of materials with high and low dielectric constants (εr = 10.2 and 2.22), which provides more advantages for both printed circuit board and MMIC design. Two "back-to-back" transition prototypes were developed, fabricated and measured in the X-band. It is shown that the relative bandwidth of 15 dB is expanded to 44.7% and 47.6% for both transitions (εr = 10.2 and 2.22), respectively, which was demonstrated for both transitions. It is noted that the measurement results are in good agreement with the simulation results, confirming the feasibility of this design.

The [24] presents the results of the study of a wideband antenna implemented using a multilayer self-packaged suspended coplanar waveguide (SCPW). The proposed antenna is designed to operate at a frequency of 5.42 GHz with a partial passband of 26.2% (4.71-6.13 GHz) and a maximum gain of 8.4 dB. The SCPW antenna was fabricated and measured, and the design was demonstrated with advantages of self-assembly, wide bandwidth, good gain, and compact size.

Thus, the analysis of existing works has shown that the conducted research indicates a wide application and significant expansion of the range of tasks solved using coplanar transmission lines in microwave devices. Moreover, optimistic expectations are noted for a significant expansion of the frequency range of the developed devices, up to the terahertz range.

However, there are no research results available related to the use of coplanar transmission lines for the production of high-speed, small-sized protective devices for antenna systems of radio-electronic equipment, capable of protecting them from short-duration powerful pulse electromagnetic interference. This circumstance necessitates research aimed at assessing the possibility of using coplanar transmission lines as a basis for implementing effective protection devices for antenna systems of radio-electronic equipment with the required frequency characteristics, while limiting the size constraints.

METHODS, RESULTS AND DISCUSSION

During the research, methods of electrodynamics theory and radio wave propagation, as well as electrical and radio engineering circuit theory, were used. Continuing the ideas developed in works [1-3, 5, 15, 25, 27-34], the superconducting coplanar transmission line will be considered as the basis for creating a device to protect antenna systems from powerful ultrashort EMI. When such a line is included in the antenna-feeder distribution path, the distribution of current and voltage in the absence of powerful EMI at the input is mainly determined by the matching of the line's wave impedance and the protection device. Under these conditions, the wave impedance of the coplanar line is determined by its main design parameters. In other words, such a state corresponds to normal operating conditions of radio electronic equipment when the EMI parameters do not exceed critical values for this coplanar line. In the opposite case, the impact of EMI leads to the destruction of superconductivity of the antenna system protection device. In this case, the distribution of current and voltage in the transmission line is determined by the superconducting, mixed, and normal states of the protection device.

The protective device based on a coplanar strip transmission line shown in Fig. 1 is a three-wire strip line with a current-carrying superconducting thin film 2 located between two semi-infinite conductive screens 1 on one side of the dielectric substrate 3 with a dielectric permeability ε_{r2} [25, 26].

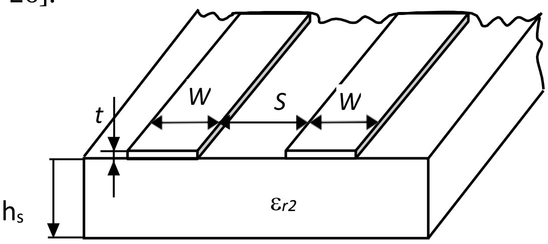

Fig. 1. Superconducting protective device based on CTL and main design parameters.

Problem statement. For the considered variants of possible operating conditions of the protection device included in the antenna-feeder path, it is necessary to solve the problem of determining the electro-physical characteristics of the coplanar line in different phase states that arise under the influence of powerful EMI and finding the conditions for reliable protection. For the first variant of conditions, it is necessary to establish a relationship between the wave impedance of the coplanar line and its design parameters, and for the second, it is necessary to assess the impact of powerful EMI on the coplanar line in its superconducting, mixed, and normal phase states.

Solution.

Case 1: there is no strong EMI at the input of the antenna feeder.

Let us consider the structural parameters of the coplanar line, and then establish the relationship between the wave impedance of the protective device and its structural parameters.

In the coplanar line, the fundamental wave is the quasi-TEM wave, although higher-order waves are possible in it, which are suppressed by connecting both screens with a conductor [25, 26]. Note that narrowing the semi-infinite screens to a finite width S^*, even with the condition $S^* < W$, weakly affects the characteristic impedance and other line parameters. For $\varepsilon_{r2} = 5$ and $S^* = W$, the wave impedance increases by only 10% compared to $S^* \to \infty$.

The substrate thickness h_s here no longer plays a prior role and at $h_s > 2S^*$ for $\varepsilon_{r2} > 9$ it can already be considered close to infinity, which allows it to be disregarded in calculations [25].

At $\frac{h}{h_s} = 0$, $S^* \neq \infty$ the wave impedance of the protective device based on CPW can be determined as follows [26]:

$$Z = \left(\sqrt{\varepsilon_{r2} + 1}\right)^{-1} 132 K_1(K), \qquad (1)$$

where $K_1(K) = \dfrac{\ln\left(2(1+\sqrt{K})/(1-\sqrt{K})\right)}{\pi}$

at $0 < K^2 \leq 0.5$,

or $K_1(K) = \dfrac{\pi}{\ln\left(2(1+\sqrt{K'})/(1-\sqrt{K'})\right)}$

at $K = \left(1 + \dfrac{2S}{W}\right)^{-1}$,

where $K' = \left(1 - K^2\right)^{1/2}$.

Effective dielectric constant is determined according to expression [26]:

$$\varepsilon_{eff_{TM}} = \frac{(\varepsilon_{r2} + 1)}{2}. \qquad (2)$$

Based on the expression (1), for the given values of Z and ε_{r2}, it is possible to determine the value of K_1. Next, using the expressions for determining K (formulas 3, 4):

$$K = \left(\frac{e^{\pi K_1} - 2)}{e^{\pi K_1} + 2)}\right)^2 \qquad (3)$$

for $1 \le K \le \infty$,
or

$$K = \left(1 - \left(\frac{e^{\pi K_1} - 2)}{e^{\pi K_1} + 2)}\right)^4\right)^{1/2} \qquad (4)$$

for $0 \le K \le 1$, (4)
the following ratio can be determined:

$$\frac{S^*}{W} = \left(\frac{1}{K - 1}\right)^2. \qquad (5)$$

Using equations (1-5), one can plot the dependence of the wave impedance of the protection device based on CPW on the ratio of its dimensions.

$\frac{W}{\left(W + 2S^*\right)}$ at $h_s \to \infty$ for different ε_{r2}.

The graph of the dependence of the characteristic impedance of a superconducting protection device based on a coplanar waveguide (CPW) on the parameter W/(W+2S) for different values of e_{r2} is shown in Fig. 2.

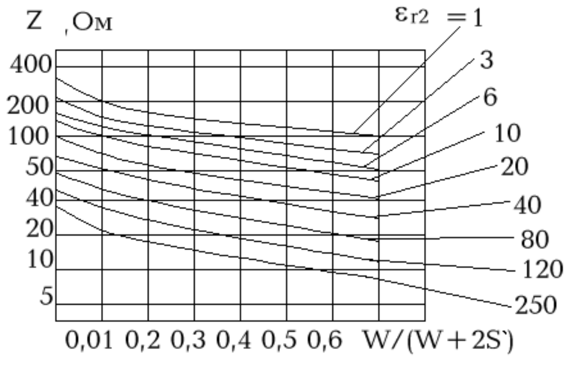

Fig. 2. Ratio of the wave impedance of a superconducting protective device based on CSL on the parameter W/(W+2S) for different values of e_{r2}.

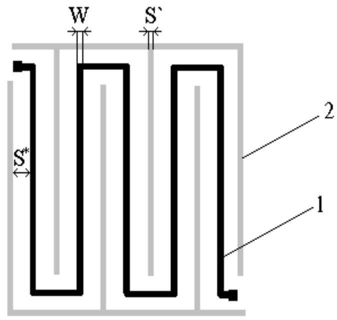

Fig. 3. Topology of a superconducting protective device based on a coplanar transmission line (1 - thin HTSC film; 2 - screen).

In addition, the period of the meander now does not depend on the thickness of the substrate.

Note that in a coplanar transmission line, there is no series parasitic capacitance, but there remains a parallel capacitance of the strip line to the C screen (see Fig. 3).

In the superconducting state, the value of capacitance C for one turn of the meander can be determined in accordance with the expression:

$$C = \frac{\varepsilon_0 \varepsilon_{r2} \varepsilon_{rN} S_c}{d\varepsilon_{rN} + \varepsilon_{r2}\lambda_1}, \qquad (6)$$

where ε_{rN} is the dielectric constant of the coplanar line in the non-superconducting state; S_c is the cross-sectional area of the meander turn;
λ_1 is the London penetration depth.

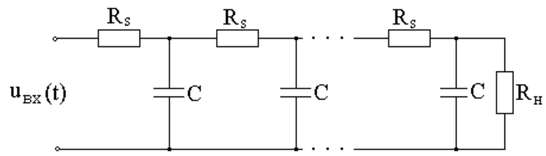

Fig.4. Equivalent circuit of a protective device based on a coplanar transmission line.

The capacitance C has a relatively small value (see Fig. 4), which makes it possible to use a protective device based on coplanar lines at frequencies up to 100 GHz and to neglect its value in calculations.

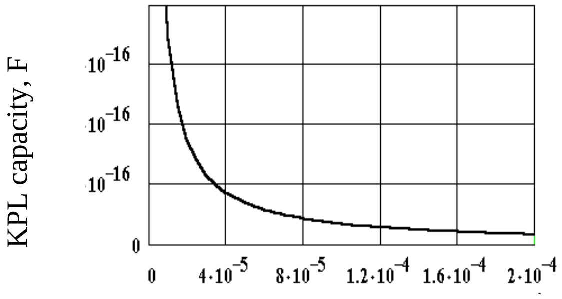

Fig. 5. Dependence of the capacitance of a protective device based on CPL on the distance between the screen and a thin HTSC film.

The approximate geometric dimensions of the protection device based on CPW wi $Z = 50$ Ohm on the substrate, e.g., made of $LaAlO_3$, are determined by the parameter $\frac{W}{W+2S^*}$ (Fig.2) and are W=10 μ, $S^* = 20$ microns, $d = 15...20$ μ the meander period $L = W + 2S^* + d = 65...70$ μ.

The dielectric strength of such a protective device is not very high, as the conducting strip and the ground plane in CPW are separated by a narrow gap of width S, and destruction of superconductivity can occur due to surface breakdown. Therefore, to increase the dielectric strength of the protective device based on CPW, it is sufficient to increase the parameter S and to use substrates with a higher e_{r2}.

The second case is when there is powerful electromagnetic interference (EMI) at the input of the antenna-feeder path. To evaluate the impact of powerful EMI on the CPW, which plays a protective role, it is necessary to solve a relatively simple problem of determining the relationships between the amplitudes and phases of the reflected and incident voltage and current waves at the end of the transmission line under the condition that it is in the superconducting, mixed, and normal phase states.

Therefore, skipping intermediate calculations, we provide the final expression for the reflection coefficient $\dot{K}$:

$$\dot{K} = \frac{Z - Z_B}{Z + Z_B}. \qquad (7)$$

For the case of small losses, the characteristic impedance of a coplanar transmission line can be approximately determined according to the expression [25]:

$$Z = \sqrt{\frac{R_a}{\omega C_o}}, \qquad (8)$$

where R_a is active resistance of CPW;

C_o is capacitance of the CPW per unit length.

An analytical expression for determining C_o taking into account that for the coplanar transmission line the condition [26] is satisfied:

$$\frac{\varepsilon_{r2}+1}{2} >> \frac{\varepsilon_{r2}-1}{2\sqrt{1+\frac{10h}{W}}} \qquad (9)$$

takes the form of:

$$C_{0_s} = \frac{\varepsilon_o \varepsilon_{r2} \varepsilon_{r_N} h \left[1 + 1,73\varepsilon_{r2}^{-0,0724} + \left(\frac{h}{S}\right)^{-0,836}\right]}{S\varepsilon_{r_N} + \varepsilon_{r2}\lambda_1}. \qquad (10)$$

We will rewrite the expression for determining R_a as:

$$R_{o_S} = \left\{ \begin{array}{c} \frac{R_S^n}{W}\left[1 - \frac{1}{4}\ln\left(\frac{Wh}{\lambda_1^2} - 1\right)\right] + \\ + \frac{R_э^n}{W\left[1 + 1,73\varepsilon_{r2}^{-0,0724} + \left(\frac{h}{S}\right)^{-0,836}\right]} \end{array} \right\}, \qquad (11)$$

where R_S^n is the surface resistance of the coplanar line, and R_e^n - is the screen surface resistance.

Note that the following expression can be used to determine the surface resistance of the coplanar line [15]:

$$R_S^n = \frac{(\omega\mu_o)^2 \sigma_N \lambda_1^4}{2h}, \qquad (12)$$

where σ_N is the specific conductivity of high-temperature superconducting film in the N-state. Since R_S^n is a small quantity, then Z according to expressions (8, 10, 11) will be determined by two parameters: C_o and R_e^n .

Therefore, having the value of R_e^n, by adjusting the ratio of $\frac{W}{h}$, it is possible to achieve equality of the wave resistances of the superconducting protection device and the line, which will ensure complete absence of reflection ($\dot{K}=0$).

When the CPW is in the mixed state, the expression for determining the wave resistance, similar to (8), can be written as:

$$Z_{S-N} = \sqrt{\frac{R_{o_{S-N}}}{\omega C_{o_{S-N}}}}, \qquad (13)$$

where $R_{o_{S-N}}$ is the active resistance of the protection device in the mixed state, and $C_{o_{S-N}}$ is the capacitance of the protection device in the mixed state. It can be shown that

$$R^n_{o_{S-N}} = \left\{ \frac{R^n_{S-N}}{W} + \frac{R_e^n \left[1+1,73\varepsilon_{r2}^{-0,0724} + \left(\frac{h}{S}\right)^{-0,836}\right]^{-1}}{W} \right\}, \qquad (14)$$

where R^n_{S-N} is the active component of the surface resistance of the coplanar transmission line (CPL) at the moment of the phase S-N transition.

The value of R^n_{S-N} can be determined based on the relation:

$$R^n_{S-N}(j\omega) = \frac{(\omega\mu_o)^2 \sigma_N \lambda_N (j\omega)^4}{2h}, \qquad (15)$$

where λ_N is the width of the normal regions of the coplanar transmission line.

The capacitance $C_{o_{S-N}}$ can be determined using a formula similar to (10), taking into account the phase state transition using the formula:

$$C^n_{o_{S-N}} = \frac{\varepsilon_o \varepsilon_{r2} \varepsilon_{r_N} h \left[1+1,73\varepsilon_{r2}^{-0,0724} + \left(\frac{h}{S}\right)^{-0,836}\right]}{S\varepsilon_{r_N} + \varepsilon_{r2}\lambda_N}. \qquad (16)$$

Now, in accordance with formulas (13), (15), and (16), let's determine the characteristic impedance of the coplanar waveguide in the mixed state:

$$Z^n_{S-N} = \sqrt{\frac{R^n_{S-N}\left[\frac{1}{j\omega C_{o1_S}} + \frac{\lambda_N}{\lambda_l}\frac{1}{\omega C_{o2_S}}\right]}{W\left[1+1,73\varepsilon_{r2}^{-0,0724} + \left(\frac{h}{S}\right)^{-0,836}\right]}}, \qquad (17)$$

where C_{o1_S} and C_{o2_S} are the capacitances per unit length at the edges of the CPW, which are due to the presence of normal regions and a ground plane.

To analyze the wave impedance of the CPW in the mixed state, expression (17) can be conveniently transformed to the form:

$$Z^n_{S-N} = \frac{R_{S-N}(j\omega)^2}{R_N}, \qquad (18)$$

where

$$K = \frac{4\lambda_l^2 I_{c2}}{h^2 I_{c1}} \sqrt{\frac{R^n_S}{R^2_{S-N}\left(C^n_{0_S}\left(W-2\lambda_N\right)\right)}}. \qquad (19)$$

Coefficient K is a dimensionless quantity. It describes the effect of the S-N phase transition of the CPW on its reactive component of wave resistance. Taking the latter into account, expression (18) will take the followimg form:

$$Z^n_{S-N} \approx \frac{R_{S-N}\omega^2}{R_N}. \qquad (20)$$

From (19), it can be seen that in the mixed state, the characteristic impedance of the CPW, as an antenna system protection device, is mainly determined by its active resistance.

In the normal state, the characteristic impedance of the CPW as per (19) can be written as follows:

$$Z^n(j\omega) \approx R_N. \qquad (21)$$

From the relations (20), (21) and (7), it follows that in the presence of powerful EMI at the input of the antenna system, leading to the destruction of superconductivity in the protection device based on the CPW, the reflection coefficient of the protective devices is mainly determined by the active resistance of the CPW, which, in turn, is determined by its design parameters.

CONCLUSIONS

1. The possibility of significant expansion of the operating frequency range of high-speed superconducting protection devices based on CPW up to 100 GHz has been demonstrated.

2. The obtained analytical relationships for evaluating the impact of intense EMI on the CPW in different phase states showed that the characteristic impedance of CPW in superconducting, mixed, and normal phase states depends on the change in the active resistance in these states, mainly determined by the design parameters of the line. These relationships are the basis for selecting and designing CPW, ensuring reliable protection for radio electronic equipment antenna systems from high-power ultra-short duration pulse EMI.

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