

WIRELESS CHANNEL DESIGN METHOD FOR A TELEPRESENCE SUIT BODY AREA NETWORK BASED ON METASURFACES

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A new period of metaverses has generated many challenges. Such relevant research areas as mirror metaverses, digital twin networks, and federations of artificial intelligence agents have become one of the most actively developed both in science and international standardization at the ITU-T, IEEE, and ISO levels. To access completely new resources and capabilities of online universes, in particular mirror metaverses, new methods based on various types of wearable telepresence suits have recently been explored and actively developed. The telepresence suit has many engineering and scientific tasks, as it is primarily the most active representative of ultra-reliable ultra-low latency communication networks (URLLC) with the requirements of the Tactile Internet. In this paper, a model of a telepresence suit based on a cylindrical coordinate system is proposed, and the problem of improving the quality of a wireless communication channel is investigated using the example of a radiating system for wearable networks (WBAN), in particular for a telepresence suit, where the possibility of using a metamaterial as a reflective layer is considered. This design makes it possible to improve the characteristics of the communication channel by improving the directivity of the emitting systems. The geometry and parameters of an SRR cell designed at a frequency of 5 GHz are presented, which is considered as a promising frequency range for the further development of WBAN networks for the first widespread use of telepresence suits.

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1 Introduction

The current decade, up to approximately 2030-2035, is shaping the face of the future: the concept of the Internet of Things, having reached the plateau of the Gartner curve, has sought to saturate markets with all kinds of solutions that make it possible to transfer business and public sector digitalization models to the level of data and digital counterparts. The International Telecommunication Union (ITU) has voiced a thesis that the next era of networks and services will be characterized by a multiverse, which is a combination of national, private, and other metaverses. This concept has begun to be implemented, and it is expected that technologies such as digital twin networks, avatars, telepresence suits, digital assets, and digital skills will make it possible to bridge gaps, including those defined in the United Nations Sustainable Development Goals (SDGs). Already at the moment, in addition to the existence of Resolution 105 of the World Telecommunication Standardization Assembly (WTSA 24) itself, there are about thirty draft ITU-T standards in 21 study group, 11 study group, avatars, metaverse structures, problems of compatibility between universes, as well as compatibility of telepresence suits.

At the same time, the problems of deep integration of artificial intelligence technologies into communication networks and services are being investigated. Such tasks cover issues of digital twins and their network, artificial intelligence (AI) agents and their federation, and artificial intelligence sandbox testing environments.

At the same time, research in the field of metaverses, in particular avatars, has identified some of the most interesting and urgent tasks of the modern decade in terms of the development of a new type of user interfaces - telepresence suits. Telepresence suits should have the necessary characteristics of Tactile Internet devices, which was fundamentally developed in the framework of research on various applications of the Internet of Things. The requirements for the tactile Internet are extremely complex and high, with a latency of 1 ms (URLLC and HURLLC) [1-2].

In conditions of imperfect data transmission medium (absence of "laboratory conditions" in the broad sense of the word), a number of natural physical conditions (wave propagation speed, interference, and much more), it is necessary to follow a systematic approach, which consists in considering the problem of delay generation from the sensor of the telepresence suit (signal registration, processing, and transmission over the on-board network), transfers from a telepresence suit to a network coordinator or base station with an appropriate wireless channel organization in a noisy environment (including parasitic radiation, absorption, etc.), primary processing on an edge server and subsequent data transmission to avatar.

A special task in this area is and will be the problem of compatibility of telepresence suits and avatars in network universes, mirror metaverses. Recently, many studies and publications have been devoted to the development of telepresence suits [3-5]. One of the publications provides a method for optimized data transmission and signal processing for telepresence suits, which also provides a comparative analysis of existing telepresence suit designs. Currently, such prototypes and solutions are known as: Tesla Suits, Senso, Perception Neuron 3, OWO Skin Haptic Suit and Kold.

The TeslaSuit telepresence suit uses a set of IMU sensors to capture movements, and also offers advanced features such as

electroneuromyography (with muscle stimulation), making it suitable, for example, for medicine. The Senso telepresence suit integrates internal and external IMU sensors, it is worth noting that it does not have tactile sensors, and is mainly focused on virtual reality (for example, in the tasks of immersion in the virtual worlds of immersive video games). The Perception Neuron 3 telepresence suit also uses IMU sensors. The OWO Skin Haptic Suit, although focused on tactile sensations and immersive services, still has limited technical capabilities. The Kold telepresence suit, developed at the Meganetlab 6G laboratory (SPbGUT), has both a sensory part and an actuating part for kinesthetic feedback, and is suitable for medical applications. It should be clarified that these telepresence suits have been developed and are being researched by research teams from different countries: Great Britain, Spain, Japan, USA, China and Russia. Naturally, the existing functionality in these telepresence suits is represented by the set that was necessary for the tasks of the relevant research. However, it is worth noting that telepresence suits represent a new type of user interface, as previously mentioned, and have a huge set of scientific tasks. These tasks can be more effectively explored taking into account the developed solutions, such as infrastructure, for example, the same Kold telepresence suit. The presented comparison highlights the diversity of existing technological advances in this field of research [3, 6].

Despite the staggering pace of development of network universe technologies, immersive technologies and the tactile Internet, there are still significant problems and scientific tasks that need to be solved for a full-fledged user interaction with virtual avatars. One of the most pressing problems is the transmission of a large amount of data (direct and reverse kinesthetic communication with the avatar based on dozens of sensors and actuators, heat and cold data transmission for subsequent regeneration, etc.) via wireless communication channels between the telepresence suit and the network coordinator, in conditions of jamming, parasitic radiation. These limitations lead to delays, inaccuracies, and reduced immersion, which is critical for applications that require precise control (positioning an avatar in a mirrored metaverse based on telepresence suit sensors), including virtual simulations, control of remote physical avatars (for example, robots based on data from a user's virtual avatar), and avatar-based interaction (avatar-avatar interaction).

2 A model of a telepresence suit

Immersive technologies allow you to partially or completely immerse yourself in the digital environment, depending on the requirements and services provided to the user. Let's consider the scenario of user interaction with an avatar in the digital universe – this is possible thanks to user devices such as a telepresence suit [7]. When a human moves, the suit changes shape, forming creases or bends. For the purpose of comfortable interaction, it is necessary to take into account the features of user movement, in addition, when designing such devices, it is necessary to take into account the influence of the body on the propagation of the radio signal.

Due to the development of immersive technologies, the design of wearable devices remains an urgent task, including the creation of new concepts of radiating devices for WBAN networks. When designing such systems, it is necessary to take into account the large number of sensors placed in the suit, from which a number

of technical tasks can be identified to preserve gain, reduce parasitic radio radiation, and suppress inter-channel communication between neighboring WBAN elements. In addition, it is important to take into account the features of the human body shape – for this it is necessary to introduce an approximating surface.

Consider the position of the sensors in the telepresence suit in the cylindrical coordinate system. Then the sensor or radiating device will have 3 coordinates $A(r, \varphi, z)$, and the r coordinate is always unchanged when moving, since the location of the device in the suit relative to the central selected axis is unchanged (FIG.1). Then we assume a change in coordinates when moving:

$$\begin{cases} r = \text{const}, \\ \varphi = \varphi_0 + \Delta\varphi, \\ z = z_0 + \Delta z. \end{cases}$$

By representing the body segments as a cylindrical coordinate system [8] and determining in advance the permissible ranges of radii of curvature and orientations of the emitting systems, it is possible to systematize the requirements for the placement of radiators on a telepresence suit with minimal losses.

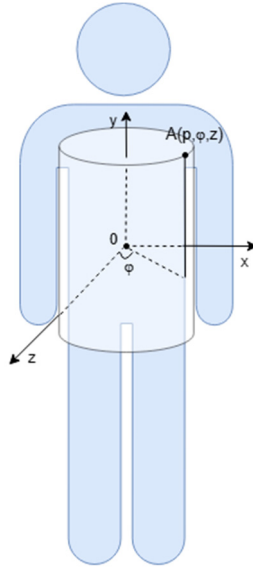


Fig. 1. Cylindrical coordinate system

To date, there are works devoted to the design of radiating systems for wearable devices. Broadband radiators can be used for WBAN systems [9]. It was noted in the work that the geometry of the body and the location of the antenna have a significant impact on the characteristics. In [10, 11], the antennas for the frequency bands of the WBAN networks are presented: 2.4GHz and 5.8 GHz, the study is carried out mainly on a planar or slightly curved substrate.

In the considered works, special attention is paid to miniaturization and improvement of the emitter matching parameters, while the influence of the user's body shape and surface curvature on the electromagnetic characteristics of antennas is considered to be limited. Most of the works [12, 13] do not take into account the peculiarities of changing the shape of emitting systems and do not consider the possibility of improving the directional characteristics and reducing back radiation.

One of the promising directions for improving the guiding properties of the emitter of wearable systems is the use of a meta-surface as a reflective surface. In [14-16], a meta-surface is used

for WBAN radiators as an improvement in the directivity index, but they do not take into account the peculiarities of the human body structure. Thus, despite the large number of works devoted to WBAN networks, the development and improvement of a compact radiator, taking into account the requirements, remains an urgent task.

In this paper, a meta-surface for a telepresence suit based on an SRR cell is proposed and investigated, implemented on a locally cylindrical substrate with radii of curvature corresponding to body segments of the user of the telepresence suit.

3 Problem statement. Antenna characteristics for WBAN systems

The antennas in WBAN networks are located directly near the human body. When researching devices for wireless wearable networks, it is necessary to take into account the electromagnetic properties of the devices that affect the user, as well as the user's influence on changes in the signal-to-noise environment. For example, an antenna integrated into a telepresence suit undergoes constant physical changes when the user moves. One of the key characteristics of antennas is the directional pattern. And when the same radiator is placed on planar and cylindrical surfaces, its radiation pattern usually differs, since the geometry of the surface changes (Fig. 2), which results in a change in the distribution of induced currents and phase ratios between elementary radiation sources at the aperture. In view of all the above, for the far zone, this is reflected in the change in the angular function of the radiation pattern.

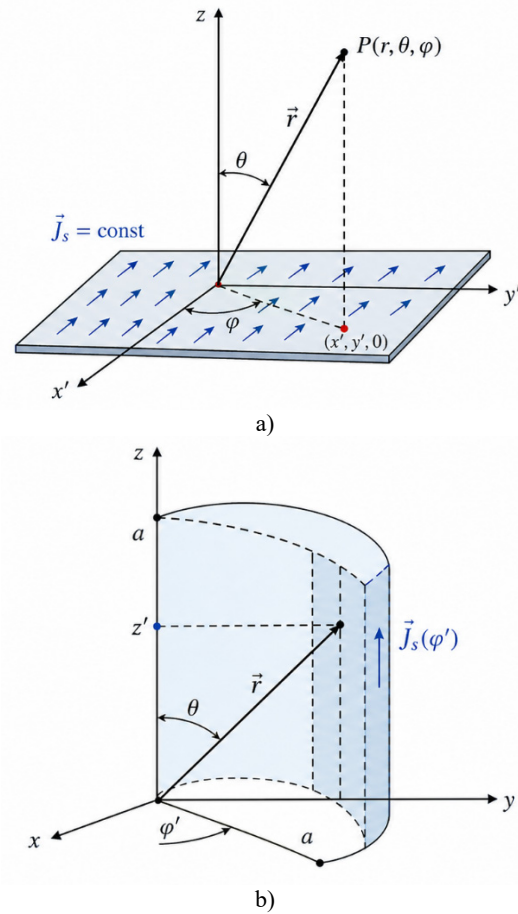


Fig. 2. Radiating surfaces a) planar b) cylindrical

For an arbitrary distribution of surface currents $\vec{J}_s(\vec{r}')$, the electromagnetic field strength in the far zone can be written as [11-12]

$$\vec{E}(\vec{r}, \theta, \varphi) \cong j\omega\mu \frac{e^{-jkr}}{4\pi r} \int_S \vec{J}_s(\vec{r}') e^{jkr \cdot \vec{r}'} dS$$

From where it is obvious that the difference between planar and cylindrical surfaces is determined by the area, the law of current distribution on the surface and the phase multiplier.

For a planar surface $z=0$, the surface point has coordinates $(x', y', 0)$, and the multiplier takes the form:

$$\vec{r} \cdot \vec{r}' = x' \sin\theta \cos\varphi + y' \sin\theta \sin\varphi$$

For a cylindrical surface of radius a , the surface point is given as $(a \cos\phi', a \sin\phi', z')$ and the multiplier is converted to the form:

$$\vec{r} \cdot \vec{r}' = a \sin\theta \cos(\varphi - \phi') + z' \cos\theta$$

The appearance of the $\cos(\varphi - \phi')$ function and a change in the current distribution over the curved surface leads to a change in the radiation pattern compared to the planar case.

Let us form the task of synthesizing the structure for the WBAN radiator in a cylindrical coordinate system (r, ϕ, z) in order to take into account the geometry of the human body. The antenna and its elements are considered as distributed over the surface of a cylinder approximating a body segment.

In addition, an important goal in the development of wearable devices is to minimize the specific absorption of electromagnetic fields (SAR) by human body tissues. According to American standards, the SAR level should not exceed 1.6 W/kg for every gram of fabric, and according to European standards, it should not exceed 2 W/kg for 10 grams of fabric. [11]

The specific absorption coefficient (SAR) in tissues is calculated [12]:

$$SAR = \frac{\sigma E^2}{\rho}$$

Where σ is the specific conductivity; E is the electric field strength and ρ is the specific density of the substance.

In wearable systems, the emitter should be compact, low-profile, and lightweight. One of the key parameters of the radiator for a telepresence suit is to take into account changes in position and orientation in space, as well as minimizing back radiation.

4 Analysis of the mathematical material structure for telepresence suits

Metamaterials include artificially created materials with a periodic structure. The properties of such cells are determined by geometric dimensions - the dimensions of the resonators and the inter-element distances are significantly less than the operating wavelength. One of the promising directions for the development of metamaterials is the use of a structure of miniature split ring frames acting as magnetic dipoles. Some types of metamaterials are presented in [20,21], for example: Edge-coupled SRR (Fig. 3a), Omega SRR (Fig. 3b) and S ring (Fig. 3c). Moreover, on the last two, a cell of a repeating shape is supplemented on the reverse side of the substrate.

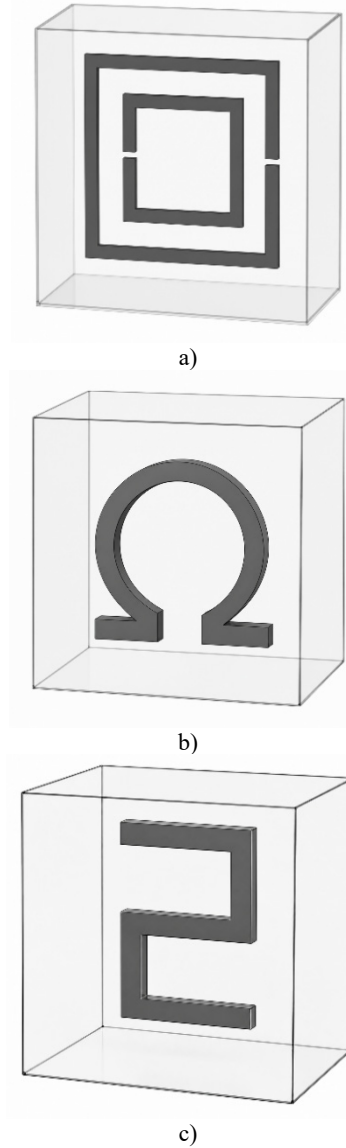


Fig. 3. a) Edge-coupled SRR b) Omega SRR c) S ring

It is known that the behavior of an electromagnetic wave is determined, among other things, by the properties of materials. Figure 4 shows the classification of materials based on the properties of their electrical and magnetic permeability. Most materials have positive characteristics $\epsilon > 0, \mu > 0$ (DPS) – these are ordinary dielectrics such as FR-4, duroid. In such media, the wave propagates according to the classical theory of wave reflection and refraction, and the refractive index and wave resistance are determined by the expressions:

$$n = \sqrt{\epsilon_r \mu_r}, Z = Z_0 \sqrt{\frac{\epsilon_r}{\mu_r}}$$

Where $\epsilon_r = \epsilon/\epsilon_0$, $\mu_r = \mu/\mu_0$, Z_0 – wave resistance of free space

The material environment $\epsilon < 0, \mu > 0$ (ENG) such indicators are observed in plasma in the frequency range when $\omega < \omega_p$, [19]:

$$\epsilon_p = 1 - \left(\frac{\omega_p}{\omega}\right)^2$$

Also, some precious metals (silver, gold) may have a negative dielectric constant in the infrared and visible regions of the spectrum.

If $\epsilon > 0$, $\mu < 0$ (MNG), some gyrotropic materials (ferrites) may have such properties in a narrow frequency range.

The material environment with properties of both negative dielectric and magnetic permeability (DNG) do not exist in nature, but they can be artificially created, such media are called metamaterials. To achieve such properties, it is necessary to create a special, periodic cell structure, the dimensions of which are smaller than the wavelength. For such media, the refractive index can be negative and equal to [20, 21]:

$$n = -\sqrt{\epsilon_r \mu_r}$$

$$n \approx -|\epsilon_r|^{1/2} |\mu_r|^{1/2} \left[1 + \frac{j}{2} \left(\frac{\epsilon''}{|\epsilon_r| \epsilon_0} + \frac{\mu''}{|\mu_r| \mu_0} \right) \right]$$

Thus, the creation of a metamaterial with the required electrodynamic properties is reduced to the synthesis of a unit cell providing the necessary electrical and magnetic characteristics.

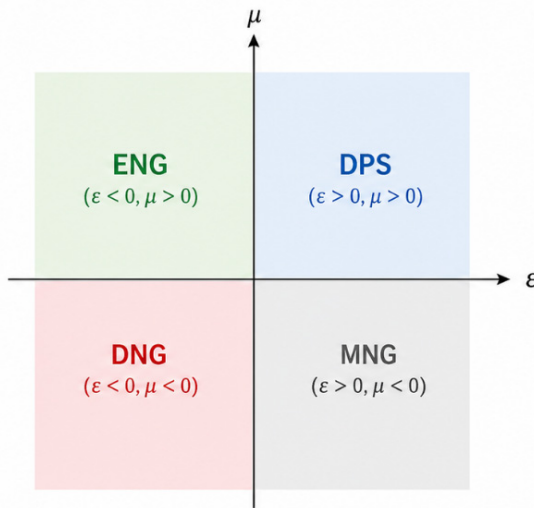


Fig. 4 Classification of materials depending on the sign of magnetic and dielectric permittivity

Since it is necessary to minimize back radiation for the purpose of this task, the material must have high-impedance properties. One of the possible embodiments of such a cell may be an SRR cell, such a structure creates a resonant magnetic reaction, which is why the material can exhibit electromagnetic properties such as negative magnetic permeability near the resonant frequency. Thus, Edge-coupled SRR is well suited for minimizing back radiation, and it can be used to obtain the magnetic and impedance characteristics necessary for the shielding properties of the system, while the cell has compact dimensions [20].

Provided that the period of the structure and the thickness of the substrate are significantly less than the radius of the substrate (in the form of a cylinder). Then such a cell can be described by a planar LC model of the first approximation. We will write the condition as:

$$p \ll R, d \ll R$$

An equivalent metasurface can be described by an LC circuit with an impedance equal to [22]:

$$Z_s(\omega) = j \frac{\omega L_{eq}}{1 - \omega^2 L_{eq} C_{eq}}$$

The surface is inductive at low frequencies and capacitive at high frequencies. The impedance is very high near the resonant frequency:

$$f_0 = \frac{1}{2\pi \sqrt{L_{eq} C_{eq}}}$$

To create a cell structure with the characteristics of an artificial magnetic conductor (AMC), the equivalent surface resistance must be significantly greater than the wave resistance of the free space at frequency f_0 . In this mode, at the transition boundary, the tangential component of the magnetic field approaches 0 (practically suppressed). As a result, the currents on the surface are in phase with the currents in the emitting element, which makes it possible to increase the directivity of the radiator and reduce the power in the direction of the user's body.

The reflection coefficient at normal incidence is related to the surface impedance by the ratio

$$\Gamma = \frac{Z_s - Z_0}{Z_s + Z_0}, \quad \phi = \arg(\Gamma)$$

Where $Z_0 \approx 377 \text{ Ohm}$, for AMC, the reflection phase should tend to 0 degrees.

5 Modeling and analysis of a metamaterial cell for a telepresence suit

Based on the structure of the SRR type metasurface, a single cell was created (Fig. 5) with substrate dimensions (9.5x9.5x1.6) mm, providing a resonant magnetic response and a high surface impedance in the 5 GHz range. Additionally, the small geometric dimensions of the SRR cell relative to the wavelength ensure a low profile of the shielding layer, which makes the selected meta-surface convenient for integration into cylindrical segments of WBAN devices.

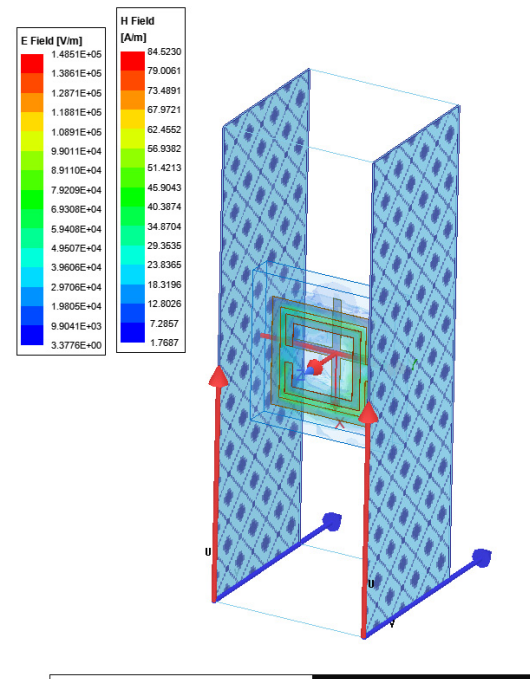


Fig. 5. Setting of boundary conditions

Based on the formed cell of the first approximation, parametric optimization was performed and a set of cell sizes corresponding to a resonant frequency of 5 GHz was selected. Figure 6 shows the S-parameters for the dimensions of the sides of the cell rings: for the outer ring it is 6.8 mm and for the inner 5 mm with a cutout of 1.05 mm.

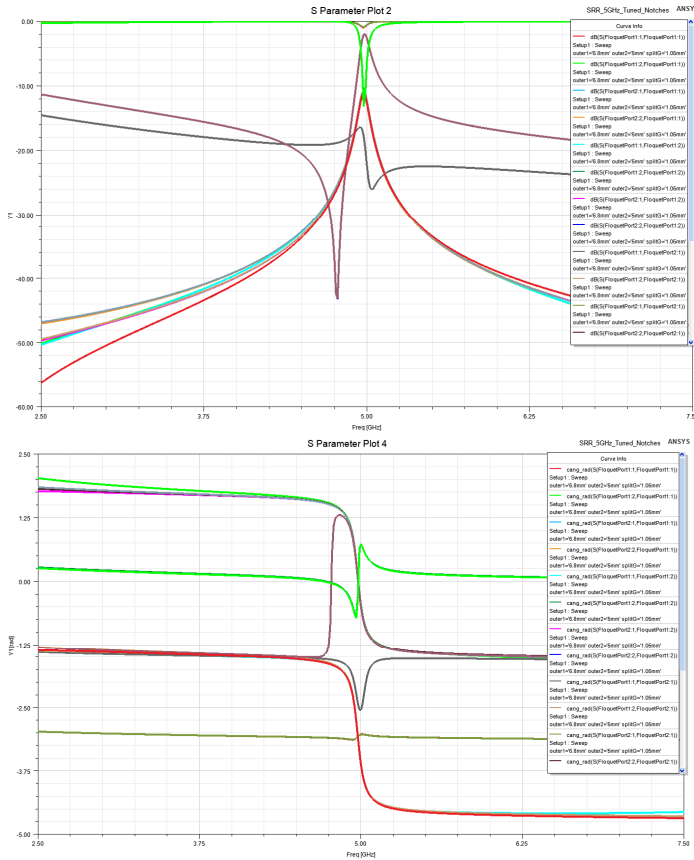


Fig. 6. S-parameters

Figure 7a shows the frequency dependences of the real $\epsilon'(f)$ and imaginary $\epsilon''(f)$ parts of the effective permittivity of the simulated metasurface. The real part (green) shows a sharp dispersion transition near the resonance: as the frequency increases, it changes monotonously and quickly passes through zero in a narrow frequency range, which indicates the formation of a region with negative effective permeability. The imaginary part (red) has a pronounced narrow maximum at the resonant frequency, reflecting an increase in losses.

Figure 7b shows the frequency dependences of the real $\mu'(f)$ and imaginary $\mu''(f)$ parts of the effective magnetic permeability. The real part (green) shows a resonant dispersion: when moving away from the resonance, its value remains close to unity, whereas in a narrow region around the resonant frequency, a sharp transition is observed and a frequency range with a negative effective magnetic permeability $\mu' < 0$ is formed. This behavior corresponds to the occurrence of a strong magnetic response due to circulating currents in the SRR structure and is a sign of a metamaterial. The imaginary part (red) has a pronounced narrow maximum in the vicinity of the resonant frequency.

Figure 7c shows the frequency dependence of the complex wave resistance of the metasurface obtained on the basis of the extracted effective parameters.

The simulation results demonstrate the possibility of creating a structure with negative parameters of dielectric and magnetic permeability in a narrow range of operating frequencies.

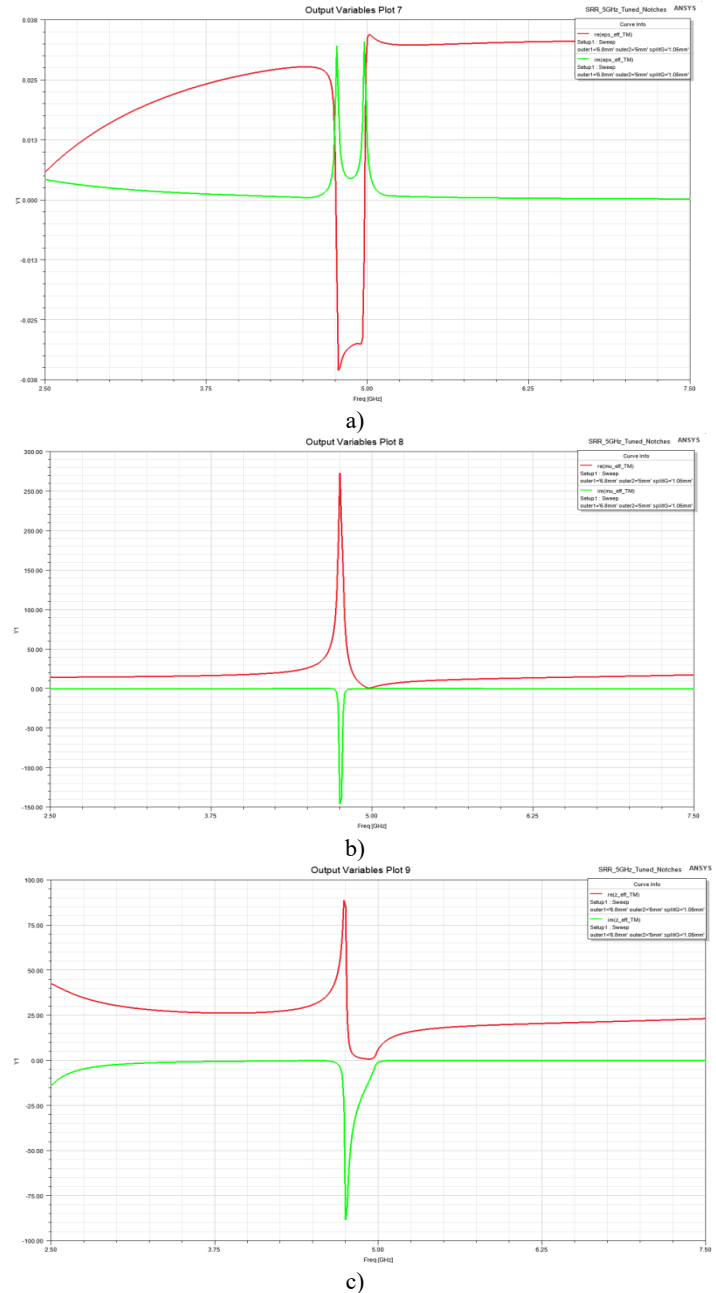


Fig. 7. Characteristics of a) dielectric constant b) magnetic permeability c) wave resistance

6 Application of a metasurface in a telepresence suit to improve the signal-to-noise ratio

One of the tasks in developing a telepresence suit wearable network is to reduce unwanted parasitic radiation that occurs due to the large number of radiating elements on the surface of the suit. By parasitic radiation we mean additional electromagnetic fields that arise.

Spurious radiation introduces additional losses into the communication channel, which reduces the signal-to-noise ratio.

Then the expression of the signal to noise ratio is:

$$SNR = \frac{P_c}{P_{III}} = \frac{P_c}{P_{TIII} + P_{III}}$$

Where P_c – the signal power, P_{TIII} – is the power converted into heat due to conductor loss and dielectric loss in the line or component, P_{III} – is the insertion loss component due to parasitic radiation, i.e., power that leaves the transmission structure as electromagnetic radiation instead of reaching the load

Various metasurfaces provide phase and amplitude control of the wavefront, which makes it possible to form directional patterns and reduce the scattering field in specified angular regions. As a result, the power of the parasitic radiation is reduced compared to the configuration of the telepresence suit without a meta-surface. This effect has been confirmed by experimental and numerical results, for example, by reducing the level of the side lobes [23] and increasing the directivity [21, 24] in the antennas of sensors with metasurfaces. As a result, the total signal-to-noise ratio in the channel increases.

Conclusions

For wearable devices of WBAN networks and telepresence suits, the use of metamaterials has a promising direction, since they have properties that affect the propagation characteristics of electromagnetic energy. The development and improvement of such systems will increase the overall signal-to-noise ratio for WBAN networks, in particular for ultra-dense networks of telepresence suits. The article presented an element of a miniature cell design at an operating frequency of 5 GHz. Modeling showed that the developed element made it possible to preserve the characteristics with varying curvature of the substrate with a radius of up to 30 mm.

Due to the optimal choice of filling cells in each node of the meta-surface, it is possible to suppress radiation in the direction of the body, reduce the level of the side and rear lobes, and simultaneously enhance radiation in the desired radiation direction. Thus, the meta-surface can serve as a thin "secondary radiator", which is a real need in the curved surfaces of telepresence suits.

The disadvantages of such a surface include a narrow range of operating frequencies, since the mode of an artificial magnetic conductor is formed near resonance and usually persists only in a limited band where the characteristics remain close to the required values. At the same time, the created meta-surface of their group of unit cells has unique properties (controlled phase response, suppression of surface waves, formation of a given radiation pattern), which in turn opens up opportunities for targeted optimization of the communication channel and the creation of compact wearable emitting systems with specified parameters.

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МЕТОД ОРГАНИЗАЦИИ БЕСПРОВОДНЫХ КАНАЛОВ НАТЕЛЬНОЙ СЕТИ КОСТЮМА ТЕЛЕПРИСУТСТВИЯ С ИСПОЛЬЗОВАНИЕМ МЕТАПОВЕРХНОСТЕЙ

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Аннотация

Эра сетевых вселенных (метавселенных) сформировала множество вызовов. Такие актуальные направления исследований, как: зеркальные метавселенные, сети цифровых двойников и федерации агентов искусственного интеллекта стали одними из активно развиваемых как в науке, так и международной стандартизации на уровне ITU-T, IEEE, ISO. Для доступа к совершенно новым ресурсам и возможностям сетевых вселенных, в частности зеркальных метавселенных, в последнее время исследуются и активно разрабатываются новые методы на основе носимых костюмов телеприсутствия различного вида. Костюм телеприсутствия обладает множеством инженерных и научных задач, так как в первую очередь он является самым активным представителем сетей URLLC - сверхнадежных сетей связи с ультрамалой задержкой с требованиями Тактильного интернета. В данной работе предложена модель костюма телеприсутствия на основе цилиндрической системы координат, а также исследована проблема повышения качества беспроводного канала связи на примере излучающей системы для нательных сетей (WBAN), в частности для костюма телеприсутствия, где в качестве отражающего слоя рассмотрена возможность применения метаматериала. Такое исполнение позволяет улучшить характеристики канала связи за счет улучшения направленности излучающих систем. Приведена геометрия и параметры SRR-ячейки, рассчитанной на частоте 5 ГГц, которая рассматривается как перспективный частотный диапазон для дальнейшего развития систем WBAN для первого широкого распространения костюмов телеприсутствия.

Ключевые слова: метавселенная, WBAN, костюм телеприсутствия, метаматериалы.

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