Artificial and natural electromagnetic structures with strongly inductive surface impedance

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Abstract. Artificial and natural electromagnetic structures with strongly inductive surface impedance are considered. The object of the research is layered structures of the "dielectric–conductor" type. The existence of impedance media with the maximum possible phase of a strongly inductive impedance in the range from a few hertz to tens of gigahertz has been established. The results of numerical modelling of the propagation of decimeter radio waves over a plane strongly inductive surface are presented, these numerical results are necessary for calculating the attenuation function $W$ and the field level $E$ of microwave electromagnetic waves.

1. Introduction

Due to the problem of surface electromagnetic waves (SEW), the study of the propagation of microwave radio waves over layered structures “dielectric – conductor” is of great importance in radiophysics. SEWs were first noted in the work of A. Sommerfeld [1]. From the formal point of view, SEWs are described by ordinary wave equations with standard boundary conditions, but they are their special solutions. At present, research on SEWs is developing quite dynamically in optic and microwave range [2,3]. In recent years, there has been an increased interest in SEW excitation at the interface between air and media with high conductivity (semiconductors and metals). These SEWs are also called surface plasmon polaritons (SPP). It should be noted that there is an electrodynamic commonality between SPP and the propagation of an electromagnetic wave over a strongly inductive impedance medium. Theoretical studies of SEW abroad were carried out by J. Wait [4]; in Russia, studies of the propagation of radio waves over layered impedance media were carried out at the Department of Radiophysics of Leningrad State University under the guidance of prof. G.I. Makarov [5].

S.A. Shchelkunov was one of the first scientists to propose an impedance approach to solving problems of electrodynamics and the theory of electrical circuits. [6]. The concept of impedance can refer to an electrical circuit, a medium, an interface, or simply a conductor. The work [7] presents an analytical review of the reference data on the use of the impedance approach in solving boundary value problems of electrodynamics for a 75-year period after M.A. Leontovich determined impedance boundary conditions for an electromagnetic field on the surface of a conducting body. In the calculations, the underlying medium must meet the impedance boundary conditions of Leontovich,
that is, the condition $|\delta|^2 << 1$ must be carried out, where $\delta$ is the normalized surface impedance of the radio path. Many problems in radio physics and radio engineering (propagation and excitation of electromagnetic waves, shielding and grounding, absorbers of electromagnetic energy, etc.) are associated with calculations of the electrodynamic characteristics of layered media. Problems of this type include: 1) calculations of the surface (input) impedance of multilayer media, taking into account the absorption and dispersion properties of materials; 2) creation of electromagnetic coatings with specified characteristics of the transmission and reflection coefficients in a wide range of frequencies and angles of incidence; 3) finding the parameters of a layered medium from the measured frequency dependence of the surface impedance.

The purpose of the article is to search artificial and natural electromagnetic structures with the maximum possible phase of a strongly inductive impedance in the class of layered models of the medium. Layered models of some natural and artificial media with strongly inductive impedance are considered.

2. Method for calculating the surface impedance of a horizontally layered medium

To describe the electromagnetic properties of a layered medium, we have adopted a model of the structure of the medium, based on the idea of the presence of electrodynamically homogeneous areas. The vertical electrical section is assumed to be horizontally layered within each area. Each layer is characterized by conductivity $\sigma_j = \rho_j / \rho$ (specific electrical resistance $\rho_j$), relative dielectric constant $\varepsilon_j$, and thickness $h_j$. The horizontally layered model of the medium is the basic fundamental model in radiophysics. The advantage of this model lies in its simplicity, on the one hand, and in the possibility of an adequate description of real radiophysical processes, on the other hand.

The software has been developed. It includes programs: 1) “Impedance” for calculating the surface impedance of layered media and statistical calculations of impedance in a given frequency range; 2) “Inverse problem” for the interpretation of radio impedance soundings [8]. The calculation technique is based on the concept of the normalized surface impedance of a plane wave on the surface of a horizontally layered structure. With the help of impedance it is possible to take into account the influence of the underlying medium on the propagation of radio waves [4,5,8]:

$$\delta = E_r / (H_r \cdot Z_0),$$

where $E_r, H_r$ – horizontal mutually perpendicular components of the electric and magnetic fields at the air-ground interface; $Z_0 = \sqrt{\mu_0 / \varepsilon_0} = 377$ Ohm is the characteristic impedance of vacuum.

The expression for the normalized surface impedance of a multilayer plane-parallel structure was used for calculations [8]:

$$\delta = \delta_0 \left( 1 - R_{12}^{(n)} \exp(-i2k_{12}h_1) \right) / \left( 1 + R_{12}^{(n)} \exp(-i2k_{12}h_1) \right),$$

where $R_{12}^{(n)} = \frac{\delta_j \alpha_j^+ - \delta_{j+1} \alpha_{j+1}^+}{\delta_j \alpha_j^+ + \delta_{j+1} \alpha_{j+1}^+}$ is the reflection coefficient at the interface between the $j$-th and $(j+1)$-th layers; $\alpha_j^+ = 1 \pm R_{j(j+1)}^{(n)} \exp(-i2k_{j,j+1}h_j)$; $k_{j,j+1} = k_0 \sqrt{\varepsilon_{j,j+1} - \sin^2 \Theta}$; $k_0 = 2\pi / \lambda$; $\delta_j = \frac{\sqrt{\varepsilon_{j,j+1} - \sin^2 \Theta} / \varepsilon_{j,j+1}}{\varepsilon_{j,j+1}}$; at $j = n$, $R_{n(n+1)}^{(n)} = 0$, $\alpha_n^+ = 1$; $\varepsilon_{j,j+1} = \varepsilon_{j} + i60\lambda\sigma_j$ is the relative complex dielectric constant; $h_j$ is the thickness of the $j$-th layer; $\Theta$ is the angle of incidence of a plane vertically polarized wave on the air-ground interface. It is assumed that the monochromatic electromagnetic wave has a time dependence $\exp(-i\omega t)$. The above relations make it possible to calculate the frequency dependences of the surface impedance of multilayer media.
3. Surface impedance of some types of layered media

Surface impedance depends on the structure of the underlying medium [4,5,7,8]. The following impedance structures are distinguished [5]:

- strongly inductive ($\text{Im} \delta < 0, |\text{Im} \delta| > |\text{Re} \delta|$);
- low inductive ($\text{Im} \delta < 0, |\text{Im} \delta| < |\text{Re} \delta|$);
- low capacitive ($\text{Im} \delta > 0, |\text{Im} \delta| < |\text{Re} \delta|$);
- strongly capacitive ($\text{Im} \delta > 0, |\text{Im} \delta| > |\text{Re} \delta|$).

It is known [5] that two-layer media of the “insulator on a conductor” and “conductor on an insulator” type with highly contrasting values $\rho_j$, $\varepsilon_j$ allow changing the impedance from strongly inductive to strongly capacitive values ($-90^\circ < \varphi_\delta < +90^\circ$). According to the theory of radio wave propagation [4,5], the field over a strongly inductive path can exceed the field over an infinitely conducting plane at some distances. The interference between spatial and surface waves also causes field oscillations. A low strongly inductive subdomain ($-45^\circ < \varphi_\delta < -72^\circ40'$) and a strongly strongly inductive subdomain ($-90^\circ < \varphi_\delta < -72^\circ40'$) are distinguished, in which there are additionally “critical” impedance phases $\varphi_{\text{cr}1} = -80^\circ$ and $\varphi_{\text{cr}2} = -83^\circ30'$. All these cases are realized only for $\varepsilon_{1c}^2 < |\varepsilon_{2c}^2|$.

In the class of natural layered media, an example of a strongly inductive structure is a two-layer “ice-sea” medium, which occupies significant areas of the World Ocean (figure 1). Ice-covered water areas meet the impedance boundary conditions in the VLF-LF-MF range, since the condition $|\delta|^2 << 1$ is carried out.

The geoelectric sections (GES) obtained on the sea sandy beaches of Asia washed by the waters of the Indian Ocean are presented in [9]. Sedimentary rock is a layered medium “dry sand - watered sea sand”, most often consisting of 3-4 layers. The generalized geoelectric section represents the “dielectric on a conductor” structure, which is very similar in its electrical and geometrical properties to the “ice-sea” medium we have previously considered. Calculations of the surface impedance frequency dependences of the layered medium “dry sand - watered sea sand” in the range of 10 kHz - 30 MHz confirmed the very close electrodynamic similarity of such structures. The main difference between such structures is the strongly inductive impedance in the range from 10 kHz to 5-10 MHz. As an example, two three-layer GESs and their frequency dependences of the surface impedance of the

Figure 1. Frequency dependences of the modulus $|\delta|$ (a) and phase $\varphi_{\delta}$ (b) of the surface impedance of a two-layer medium “ice-sea”. The numbers on the graphs are the thickness of the ice layer.
medium “dry sand - watered sea sand” in the range of 10 kHz - 30 MHz are presented in figure 2. The “dry sand - watered sea sand” medium is analogous to the “ice-sea” structure in the VLF-HF range. (figure 2).

As a result of the search carried out in natural media, the existence of layered media with the maximum possible phase of strongly inductive impedance in the range from a few kilohertz to tens of megahertz was established. Let's note the wide distribution of beaches on all oceans and seas of the Earth. Consequently, such structures are typical for large areas of the Earth's surface and must be taken into account when calculating coastal refraction of the “land-sea” type in radio systems (direction finding and energy).

Let us consider the results of modeling the surface impedance of a thin three-layer medium “dielectric on a metal magnetic base” in a wide frequency range from 1 Hz to 10 GHz, corresponding to the real structure “paint layer on a steel sheet” (figure 3). Magnetic permeability of the substrate will be changed from 1 to 100 and up to 10000. Calculations show that a two-layer dielectric film “primer-paint” with a thickness of 0.5 mm shifts the impedance phase into the strongly inductive region already at frequencies from 100 Hz and above to 10 GHz. The impedance modulus satisfies the impedance boundary conditions over the entire frequency range. The impedance phase shows that in the class of layered natural and artificial media there are media with the maximum possible impedance phase values of strongly inductive impedance close to $-90^\circ$.

The obtained values of the surface impedance indicate that the conditions for the propagation of electromagnetic waves over such structures in a wide range of radio waves will have features due to the appearance of a surface electromagnetic wave (SEW). Based on the experimentally proven fact of the existence of a SEW [10] and the principle of electromagnetic similarity, the obtained calculations of the surface impedance make it possible to theoretically substantiate the existence of an SEW over the “dielectric on a conductor” structure in the decimeter range of radio waves.
Figure 3. Frequency dependences of the modulus $|\delta|$ (a) and phase $\varphi_\delta$ (b) of the surface impedance of a three-layer medium “dielectric on a metal magnetic base”.

Numerical modelling of the propagation conditions of radio waves over a model hypothetical homogeneous radio path for a GSM 1800 MHz cellular communication frequency showed the appearance of a SEW over the “dielectric – conductor” structure. Figure 4 shows the calculated values of the modulus of the field attenuation function $|W|$ and the field level $E$ above a flat strongly inductive surface “dielectric on a metal magnetic base” for radiation power of 1 W.

Figure 4. Calculated values of the modulus of the field attenuation function $|W|$ (a) and the field level $E$ (b) above a plane strongly inductive surface “dielectric on a metal magnetic base” at a frequency of 1800 MHz. The radiation power is 1 W.

It can be seen from the graphs that in layered media with strongly inductive impedance, it is possible to achieve a large, purely electrodynamic in nature, amplification of the electromagnetic field. A strong dependence of the field amplification and the SEW propagation distance on the impedance phase has been established. Modelling has shown that the propagation of SEW in the decimeter range is better at closer distances from the emitter. That is, the presence of a two-layer dielectric film “primer-paint” with a thickness of 0.5 mm increases the field near the surface at short distances and decreases the field near the surface at long distances relative to the conductor. At the considered frequency, interference is observed between the spatial and surface waves, which causes oscillations of the field level. In practical terms, the effect of the appearance of SEW and interference can take place during the propagation of radio waves not only in cellular systems (GSM and CDMA) in the 450, 900 and 1800 MHz ranges, WiFi (2300 MHz), but also in the GPS radio navigation system L1 = 1575.42 MHz and L2 = 1227.6 MHz and GLONASS over real structures, for example, over traffic...
jams (fractal radio path). It is necessary to carry out additional experiments and propose new technical solutions based on the effect of the appearance of SEW for radio systems of the UHF-microwave ranges. Methods for measuring surface impedance in the microwave range should also be improved [11].

4. Conclusion

As a result of the search carried out among artificial and natural electromagnetic media, the existence of layered structures with the maximum possible phase of a strongly inductive impedance in the range from a few hertz to tens of gigahertz was established. Based on the results of modelling the surface impedance of a thin three-layer medium “dielectric on a metal magnetic base” in the frequency range from 1 Hz to 10 GHz, it was found that a two-layer dielectric film “primer-paint” 0.5 mm thick shifts the impedance phase to a strongly inductive region already at frequencies from 100 Hz and above. The impedance modulus carries out the impedance boundary conditions over the entire frequency range. The phase impedance is close to \(-90^\circ\). It is shown that there is a SEW above strongly inductive structures. This unique electrodynamic process played and plays an important, and sometimes a decisive role in natural physical and physico-chemical processes on the surface of layered media in a wide range of electromagnetic waves from millihertz to terahertz. The accumulated data on SEWs make it possible to obtain new fundamental knowledge, the results of which can be used on real radio links. The introduction of new results can be carried out both for new microwave radio systems and for complex technologies, for example, in the field of metamaterials.

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