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ELECTRODYNAMIC ALGORITHM FOR CALCULATION OF THE REFLECTIVE ELEMENT OF A RECONFIGURABLE INTELLIGENT SURFACES

The article is devoted to the study of a new approach to calculating the reflective element of a reconfigured intelligent surface. The solution of the electrodynamic problem is carried out based on a conditional division of the entire region of determination of the electromagnetic field in a single reflective element into two regions. The correctness of the application of the proposed approach for calculating the characteristics of a single reflective element is shown.

In this article, a calculation of a single reflective element of a reconfigured intelligent surface is carried out. The numerical convergence of the proposed approach for reflection coefficients is investigated when the order of truncation of the system of linear algebraic equations increases. It is obtained that the modulus of the reflection coefficient R_{10} *coincides with the exact solution. That is, for the case of scanning in the H-plane for all scanning angles, good convergence of the solution to the problem is obtained.*

The aim of the work *is to develop methods for calculating waveguide reflective elements of reconfigurable intelligent surfaces.*

The methodology *consists of the conditional division of the entire area of determination of the electromagnetic field into two areas and the application of the integral equation method.*

The scientific novelty *lies in the fact that we have shown the correctness of applying a new approach to calculating a single reflective element of a reconfigured intelligent surface.*

The conclusions *can be formulated as follows. The feasibility of using a waveguide reflective element in reconfigurable intelligent surfaces is shown. The use of a rigorous electrodynamic calculation of this structure based on the integral equation method is proposed. The correctness of the algorithm is shown by a boundary transition to a known exact solution. This allows us to recommend the proposed methodology for building reconfigurable intelligent surfaces in 5G and 6G.*

Key words: *reconfigured intelligent surface, reflective element, integral equation method, reflection coefficient, numerical convergence, wireless network.*

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ЕЛЕКТРОДИНАМІЧНИЙ АЛГОРИТМ РОЗРАХУНКУ ВІДБИВАЮЧОГО ЕЛЕМЕНТУ РЕКОНФІГУРОВАНОЇ ІНТЕЛЕКТУАЛЬНОЇ ПОВЕРХНІ

Статтю присвячено дослідженню нового підходу до розрахунку відбиваючого елементу реконфігурованої інтелектуальної поверхні. Розв'язок електродинамічної задачі проводиться на основі умовного розподілу всієї області визначення електромагнітного поля в одиничному відбиваючому елементі на дві області. В даному підході використовується метод інтегрального рівняння. Показана коректність застосування запропонованого підходу для розрахунку характеристик поодинокого відбиваючого елементу.

В даній статті проведено розрахунок поодинокого відбиваючого елементу реконфігурованої інтелектуальної поверхні. Досліджена чисельна збіжність запропонованого підходу для коефіцієнтів відбиття R_{10} при збільшенні порядку усічення системи лінійних алгебраїчних рівнянь. Отримано, що модуль коефіцієнта відбиття співпадає із точним рішенням. Тобто, для випадку сканування в Н-площині для всіх кутів сканування отримана гарна збіжність рішення задачі.

Мета роботи *полягає в розробці методу розрахунку хвилеводного відбиваючого елементу реконфігурованої інтелектуальної поверхні.*

Методологія *полягає в умовному розділі всієї області визначення електромагнітного поля на дві області та застосуванні метода інтегрального рівняння.*

Наукова новизна *полягає в тому, що ми показали коректність застосування нового підходу для розрахунку поодинокого відбиваючого елементу реконфігурованої інтелектуальної поверхні.*

Висновки *можна сформулювати таким чином. Показано, доцільність використання хвилеводного відбиваючого елементу в реконфігурованих інтелектуальних поверхнях. Запропоновано використання строгого електродинамічного розрахунку даної структури на основі метода інтегрального рівняння. Показана коректність алгоритму шляхом межового переходу до відомого точного рішення. Це дозволяє рекомендувати запропоновану методику для побудови реконфігурованих інтелектуальних поверхонь в 5G та 6G.*

Ключові слова: *реконфігурована інтелектуальна поверхня, відбиваючий елемент, метод інтегрального рівняння, коефіцієнт відбиття, чисельна збіжність, бездротова мережа.*

Relevance of the problem. Reconfigurable intelligent surfaces (RISs) are known as intelligent reflecting surfaces (IRSs), or large intelligent surfaces (LISs), have received significant attention for their potential to enhance the capacity and coverage of wireless networks by smartly reconfiguring the wireless propagation environment. Therefore, RISs are considered a promising technology for the sixth generation (6G) of communication networks.

Analysis of recent research and publications. The development of 5G mobile communications has led to the implementation of massive MIMO techniques at base stations. Although this technology allows you to control the beam, it fails to solve the blockage problem. The problem of blocking electromagnetic waves becomes particularly acute in large cities with dense buildings (Basar E., 2021; Sharma T., 2021). More densely deployed base stations can help eliminate blockages and fill coverage holes, but this is a costly solution both in terms of its infrastructure (and backhaul requirements) and power consumption. To solve this problem, you can use reconfigurable intelligent surfaces (RIS), which allow you to get rid of the above-mentioned problem. A RIS is a flat surface consisting of an array of passive reflective elements, each of which can be controlled by imposing a required phase shift on the input signal (Tapio V., 2021; Liu Y., 2021). Based on the specific materials of the reflecting elements, the RIS can be classified into antenna-array-based (Tan X., 2016) and metasurfacebased structures (Hassouna S., 2023). By carefully adjusting the phase shifts of all the reflecting elements, the reflected signals can be reconfigured to propagate towards their desired directions.

In RIS, surfaces can control the propagation of electromagnetic incident waves in a programmable smart radio environment (Liu R., 2023; Pan C., 2021). Therefore, RIS is an artificial surface of electromagnetic (EM) material, electronically controlled with integrated electronics (Renzo M. D., 2022). It is a novel and cost-effective solution to obtain enhanced energy and spectral efficiency for wireless communications. RISs can be installed on large flat surfaces (e.g., walls or ceilings indoors, buildings or signage outdoors) to reflect radio-frequency energy around obstacles and create a virtual line-of-sight propagation path between a microwave source and the destination (Yildirim I., 2021; Ellingson S. W., 2021).

The communication model for RIS can be built based on a phased array antenna (Magro V. I., 2023). Local design at the unit cell level is a widely used method to determine the reflection and transmission characteristics of RIS. The accuracy of the RIS model can be improved by applying the integral equation method, which has already been tested for the calculation of waveguide antenna arrays. Improvement of RIS properties can be achieved by using different designs of reflective elements (Magro V. I., 2022). However, in the general case, the calculation of a two-dimensional waveguide antenna with a complex shaped reflective element requires complex modeling. Thus, RIS can be used to support cellular networks beyond cellular 5G networks; for RIS-assisted indoor communications; in case of RISs in unmanned systems for smart city; in case of RISs in intelligent IoT networks.

The purpose of research is to develop methods for calculating waveguide reflective elements of reconfigurable intelligent surfaces.

Presentation of the main research material. Let's take a closer look at the reflective element of the intelligent reflective surface, which has the form of an open end of a waveguide with a diaphragm inside. These elements form a two-dimensional reflective surface of the appropriate size. The angle in which electromagnetic energy is reflected is determined by the phase shift between adjacent elements. To simplify the calculation, we will use

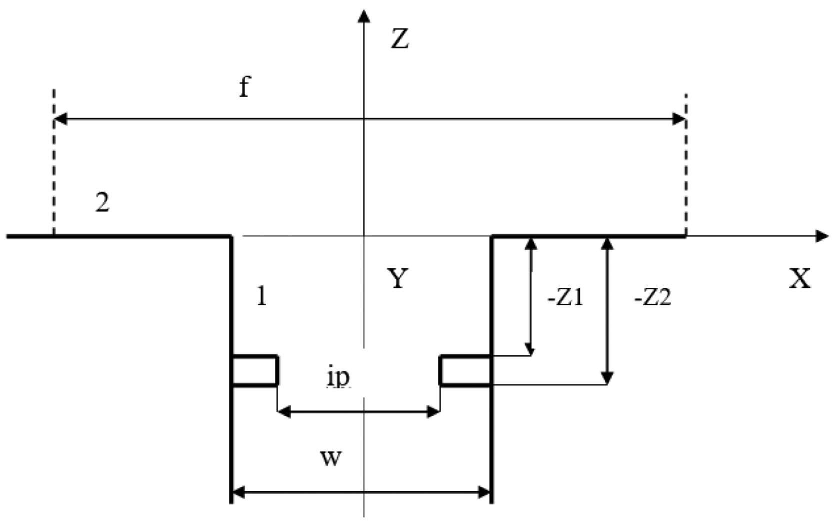

Fig. 1. One cell of an intelligent reflective surface having a finite thickness diaphragm inside the waveguide

the method used to calculate an infinite phased antenna array. A feature of the single element considered in this work is the presence of a finite-thickness diaphragm located inside the waveguide. We will consider the case of reception-reflection of an electromagnetic wave in the H-plane (the electric field strength vector is directed along the OY axis), Fig.1. We conditionally divide the domain of definition of the electromagnetic field into two regions: 1 – section of the waveguide starting at the phase control element and ending in the plane of the reflecting surface $-a/2 \le x \le a/2$, $-\infty \le z \le 0$; 2 – Floquet channel $-f/2 \le x \le f/2$, $0 \le z \le \infty$.

Based on the second Green's formula, the integral representation for the complete field of the second region has the form:

$$E_y^1(x,z) = E_{y\,ext}(x,z) + \\ + \int_{-w/2}^{-ip/2} \left[G^1(x,z;x',-z2) \frac{\partial E_y^1(x',z')}{\partial z'} \bigg|_{z'=-z2} - \\ -G^1(x,z;x',-z1) \frac{\partial E_y^1(x',z')}{\partial z'} \bigg|_{z'=-z1} \right] dx' + \\ + \int_{ip/2}^{w/2} \left[G^1(x,z;x',-z2) \frac{\partial E_y^1(x',z')}{\partial z'} \bigg|_{z'=-z2} - \\ -G^1(x,z;x',-z1) \frac{\partial E_y^1(x',z')}{\partial z'} \bigg|_{z'=-z1} \right] dx' + \\ + \int_{-z2}^{-z1} \left[-G^1(x,z;-ip/2,z') \frac{\partial E_y^1(x',z')}{\partial x'} \bigg|_{x'=-ip/2} + \\ +G^1(x,z;ip/2,z') \frac{\partial E_y^1(x',z')}{\partial x'} \bigg|_{x'=ip/2} \right] dz' - \\ - \int_{-w/2}^{w/2} E_y^1(x',0) \frac{\partial G^1(x',0)}{\partial z'} \bigg|_{z'=0} dx'.$$

When recording the integral representation, the extended domain method was used to consider the presence of a diaphragm in the waveguide. Here $G^1(x, z; x', z')$ is Green's function for a semi-infinite domain with Dirichlet boundary conditions at $z = 0$.

$$G^1(x,z;x',z') = \\ = \sum_{mg=1}^{\infty} d1_{mg}(x) d1_{mg}(x') \frac{1}{jcg1_{mg}} \begin{cases} e^{jcg1_{mg} z} shjcg1_{ng} z', z \ge z' \\ e^{jcg1_{mg} z'} shjcg1_{ng} z, z \prec z' \end{cases}.$$

Here $d1_{mg}(x)$ is a transverse function of the waveguide; $cg1_{mg}$ are propagation constants in the waveguide.

The electric field strength in region 1 is represented as:

$$E_y^1(x,z) = E_{y\,ext}(x,z) + \sum_{m=1}^{\infty} R_m d1_m(x) e^{j\,cg1_m z},$$

here $E_{y\,ext}(x, z)$ is electric field strength of incident H_{10} waves in a waveguide; R_m are the complex reflection coefficients that need to be found.

The electric field strength of region 2 is represented as:

$$E_y^2(x,z) = \sum_{m=-\infty}^{\infty} T_{mf} df_{mf}(x) e^{-j\,cgfmf\,z}.$$

Here T_{mf} complex coefficients of passage of region 2; $df_{mf}(x)$ are transverse eigenfunctions of the Floquet channel (Amitay N., 1974); $cgfmf$ are constant propagation in the radiation field.

We use the boundary conditions for the electric and magnetic field strengths at the junction of the regions at $z = 0$. We obtain a system of functional equations

$$\sum_{mf=-\infty}^{\infty} T_{mf} df_{mf}(x) = E_{y\,ext}(x,0) + \sum_{m=1}^{\infty} \sum_{mg=1}^{\infty} R_m f1m_{mg} d1_{mg}(x).$$

$$\sum_{mf=-\infty}^{\infty} T_{mf} cgf_{mf} df_{mf}(x) = \\ = \frac{\partial E_{y\,ext}(x,z)}{\partial z} \bigg|_{z=0} + \sum_{m=1}^{\infty} \sum_{mg=1}^{\infty} R_m f2m_{mg} d1_{mg}(x).$$

Here $f1m_{mg}$ and $f2m_{mg}$ are complex functions that are obtained because of mathematical operations.

To eliminate the dependence on transverse functions in the obtained equations, we multiply the equation for the electric field strength (the first equation) by the function $df^*_{mfv}(x)$ and integrate from $-f/2$ to $f/2$; multiply the equation for the magnetic field strength (second equation) by $d1_{mv}(x)$ and integrate from $-w/2$ to $w/2$.

As a result, we obtain a system of linear algebraic equations with respect to unknown complex coefficients T_{mf} and R_m:

$$\delta mf_{mfv} T_{mfv} + \sum_{m=1}^{\infty} R_m \left\{ \sum_{mg=1}^{\infty} f1m_{mg} f3mg_{mfv} \right\} = f41_{mfv}.$$

$$\sum_{mf=-\infty}^{\infty} T_{mf} f5mv_{mf} + \sum_{m=1}^{\infty} R_m f2m_{mv} = \delta 1_{mv} f61_{mv}.$$

Here $f3mg_{mfv}$, $f41_{mfv}$, $f5mv_{mf}$, $f61_{mv}$ are complex functions that are obtained as a result of performing mathematical operations; δmf_{mfv}, $\delta 1_{mv}$ are Kronecker symbols.

To verify the proposed calculation algorithm, a test check of the limiting cases was performed. A study of the convergence of the solution for the modulus and phase of the reflection coefficient R_{10} of incident H_{10} waves in waveguides at $f/\lambda = 0.5714$; $w/\lambda = 0.5714$; $\theta = 2.87°$ (scanning angle) was performed, Table 1. The same number of M wave types were selected in the waveguides and

Table 1

Convergence of the solution for the modulus and phase of the reflection coefficient R_{10} of incident waves H_{10} in waveguides

M	$\|R_{10}\|$	phase, deg.
	$\theta = \mathbf{2.87°}$	
3	0,3298	160,64
5	0.3401	158,11
7	0.3433	157,22
9	0.3447	156,80
11	0.3455	156,56
13	0.3459	156,41
15	0.3462	156,30
17	0.3464	156,23
19	0.3465	156,18

in the radiation region. For example, three types of modes in the waveguide (H_{10}, H_{20}, H_{30}) and three harmonics of the Floquet channel (–01, 00, 10) were chosen. For this case, the exact solution is presented in (Amitay N., 1974). It is respectively 0,347 for the modulus and 155,9 for the phase of the reflection coefficient.

Conclusions and prospects for further research. Thus, this publication provides an overview of the development prospects of reconfigurable intelligent surfaces for 5G and 6G. This technology allows you to control the direction of electromagnetic wave propagation, which allows you to get rid of signal blocking and accordingly expand the service areas of the wireless network. A major challenge today is the creation of effective methods for calculating reflective elements of RIS. The proposed calculation method makes it possible to develop complex waveguide reflective elements and improve the accuracy of the calculation. In the future, it is planned to conduct research aimed at generalizing the methodology for calculating reflective elements of RIS.

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