УДК 621.372

Scattering of Electromagnetic Waveson Lattices of Rectangular Dielectric Resonators

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The c-functions that determine the degree of influence of an external exciting electromagnetic field on a rectangular dielectric resonator (DR) in open space are calculated and investigated. The presence of directions with "zero" projection of the exciting electromagnetic field onto the DR field is shown. Using the perturbation theory, the spatial distribution of the scattered electromagnetic fields, which arises when a plane electromagnetic wave of p-, or s-type, is incident on a square lattice of rectangular dielectric resonators is studied. An electromagnetic model of scattering on a rectangular DR lattice is constructed. The appearance of a reflected and shadow lobe during scattering by a lattice of rectangular DRs with basic magnetic modes is demonstrated. The features of scattering by a cubic lattice with degenerate magnetic oscillations of the main type are investigated. It is shown that the degeneracy of the eigenoscillations of the resonators leads to a more complex scattering pattern: the appearance of additional lobes, as well as a change in their shape. It is noted that the shape of the spatial distribution of the scattered electromagnetic field of the grating can change noticeably with frequency variation within the frequency band of coupled oscillations of the resonators of the lattice. The obtained practical simulation results make it possible to significantly reduce the computation time and optimize complex multi-cavity structures of microwave and optical communication systems that simultaneously perform the functions of separation or combining of channels.

Key words: scattering; lattice; rectangular dielectric resonator; modeling; c-function; scattering amplitude

DOI: 10.20535/RADAP.2021.84.5-10

Introduction

Today, lattices of rectangular dielectric resonators are actively studied as a basis for creating new metamaterials [1–3, 5, 10, 12], as guiding structures for manipulating photons in the terahertz range [9], as well as nanoantennas [6, 8], splitters [4, 7, 12], and in the microwave range as filters [11] and antennas [13–16, 18, 19]. The calculation and theoretical analysis of the properties of such lattices is carried out based on numerical solutions of Maxwell's equations, which complicate the understanding of the physical principles defining behavior of such complex structures of coupled Dielectric Resonators (DRs). The development of the physical theory of scattering by complex structures of DRs [8, 17] made it possible not only to clarify their behavior in various structures, but also showed the effectiveness of this approach to a unified method for describing various devices in the microwave and optical ranges. The proposed theory was mainly used to describe DR of disk and spherical shapes; rectangular dielectric resonators were not considered. The analysis of scattering theory for rectangular DRs based on perturbation theory was first carried out in [14]. In order to extend this theory to complex structures of rectangular DRs in open space, it is necessary to first calculate the coupling coefficients of this type of resonators [2]. The purpose of this work is to calculate and analyze the expansion coefficients of the electromagnetic field of plane wave on a rectangular DR in the open space, as well as create an electrodynamic model of a lattice of rectangular DRs. Study of the characteristics of scattering of electromagnetic waves on lattices of rectangular dielectric resonators.

1 Statement of the problem

The purpose of this article is to calculate and analysis the electromagnetic field scattered by planar lattices of rectangular DRs with lowest eigenoscillations of magnetic type. Representing the solution to the problem of scattering in the form [8], it is necessary to calculate the c-function for a rectangular DR for the case of a plane wave incidence in open space.

2 Calculation c-functions for the plain electromagnetic waves and rectangular DRs

Let a plain electromagnetic wave $\left(\vec{E}^{+},\vec{H}^{+}\right)$ falls on a rectangular DR at the frequency of its magnetic oscillation H_{nml} (Fig.1, a).

$$\begin{aligned}\vec{E}^{+} &= \vec{E}_0 e^{-ik_0(x\cos\gamma_1+y\cos\gamma_2+z\cos\gamma_3)};\\ \vec{H}^{+} &= \vec{H}_0 e^{-ik_0(x\cos\gamma_1+y\cos\gamma_2+z\cos\gamma_3)};\\ \vec{E}_0 &= E_0(\vec{x}_0\cos\alpha_1+\vec{y}_0\cos\alpha_2+\vec{z}_0\cos\alpha_3);\\ \vec{H}_0 &= \frac{E_0}{w_0}(\vec{x}_0\cos\beta_1+\vec{y}_0\cos\beta_2+\vec{z}_0\cos\beta_3),\end{aligned}\quad(1)$$

where $(\vec{x}_0,\vec{y}_0,\vec{z}_0)$ – are the unit vectors of a rectangular coordinate system $(x,\ y,\ z)$, $\vec{E}_0$ – amplitude vector, and $w_0=\sqrt{\mu_0/\varepsilon_0}$ – is the wave impedance of the open space. Angles $(\alpha_1,\alpha_2,\alpha_3)$, $(\beta_1,\beta_2,\beta_3)$ define the spatial orientation of the electric and the magnetic field vectors, respectively, and the $(\gamma_1,\gamma_2,\gamma_3)$ – defines a direction of the wave expansion. Let us calculate the projection of the electromagnetic field $(\vec{E}^{+},\vec{H}^{+})$ [8] onto the field of eigenoscillations of a rectangular resonator $(\vec{e},\vec{h})$ with magnetic oscillations H_{nml} in local DR coordinate system (x',y',z') [18]:

$$\begin{aligned}
e_{x'} &= -h_1\frac{i\omega\mu_0}{k_1^2-\beta_z^2}\beta_y\begin{pmatrix}\sin\beta_x x'\\ \cos\beta_x x'\end{pmatrix}\begin{bmatrix}\cos\beta_y y'\\ -\sin\beta_y y'\end{bmatrix}\begin{Bmatrix}\sin\beta_z z'\\ \cos\beta_z z'\end{Bmatrix};\\
e_y &= h_1\frac{i\omega\mu_0}{k_1^2-\beta_z^2}\beta_x\begin{pmatrix}\cos\beta_x x'\\ -\sin\beta_x x'\end{pmatrix}\begin{bmatrix}\sin\beta_y y'\\ \cos\beta_y y'\end{bmatrix}\begin{Bmatrix}\sin\beta_z z'\\ \cos\beta_z z'\end{Bmatrix};\\
e_z &= 0;\\
h_x &= h_1\frac{1}{k_1^2-\beta_z^2}\beta_x\beta_z\begin{pmatrix}\cos\beta_x x'\\ -\sin\beta_x x'\end{pmatrix}\begin{bmatrix}\sin\beta_y y'\\ \cos\beta_y y'\end{bmatrix}\begin{Bmatrix}\cos\beta_z z'\\ -\sin\beta_z z'\end{Bmatrix};\\
h_y &= h_1\frac{1}{k_1^2-\beta_z^2}\beta_y\beta_z\begin{pmatrix}\sin\beta_x x'\\ \cos\beta_x x'\end{pmatrix}\begin{bmatrix}\cos\beta_y y'\\ -\sin\beta_y y'\end{bmatrix}\begin{Bmatrix}\cos\beta_z z'\\ -\sin\beta_z z'\end{Bmatrix};\\
h_z &= h_1\begin{pmatrix}\sin\beta_x x'\\ \cos\beta_x x'\end{pmatrix}\begin{bmatrix}\sin\beta_y y'\\ \cos\beta_y y'\end{bmatrix}\begin{Bmatrix}\sin\beta_z z'\\ \cos\beta_z z'\end{Bmatrix}.
\end{aligned}\quad(2)$$

Here $k_0=\omega\sqrt{\mu_0\varepsilon_0}$, $k_1=\omega\sqrt{\mu_0\varepsilon_1}$ and $(\beta_x,\beta_y,\beta_z)$ – are the wave numbers; h_1 – is the amplitude; ω – is the circular frequency; μ_0 – is the magnetic permeability; ε_0, ε_1 – is the dielectric permittivity of the external space and resonator, respectively.

We need to calculate in general the integrals for $t=1,2,\ldots,N$ DR of the lattice:

$$c_t^{+}=-1/2\oint\limits_{s_t}\{[\vec{e}_t,\vec{n}](\vec{H}^{+})^{*}+[\vec{n},\vec{h}_t](\vec{E}^{+})^{*}\}ds,\quad(3)$$

where S_t is the surface of the t-th DR. For a rectangular DR, it is more convenient to bring integral (3) to the form with an accuracy $1/Q_\Sigma$:

$$c_t^{+}\approx i/2\omega(\varepsilon_1-\varepsilon_0)\int\limits_{V_t}(\vec{e}_t,(\vec{E}^{+})^{*})dv.\quad(4)$$

Here Q_Σ – is the resonator Q-factor.

The results of calculating the integral (4) in the t-DR center coordinate system (x',y',z') are presented in the form:

a) for X-position (Fig.1, b) and for the p-polarization of the incident wave:

$$\begin{aligned}c^{+}=c_0\cdot[\beta_y\omega_x(\cos\gamma_2)\varpi_y(\cos\gamma_3)\cdot\frac{1}{M}\cos\gamma_2\cos\gamma_3+\\ +\beta_x\varpi_x(\cos\gamma_2)\omega_y(\cos\gamma_3)M]\omega_z(\cos\gamma_1),\end{aligned}\quad(5)$$

s-polarization of the incident wave:

$$c^{+}=c_0\cdot\beta_y\omega_x(\cos\gamma_2)\varpi_y(\cos\gamma_3)\omega_z(\cos\gamma_1)\cdot\frac{1}{M}\cos\gamma_1;\quad(6)$$

b) for Y-position (Fig.1, c) and for the p-polarization of the incident wave:

$$\begin{aligned}c^{+}=c_0\cdot[\beta_y\omega_x(\cos\gamma_1)\varpi_y(\cos\gamma_3)\cdot\frac{1}{M}\cos\gamma_1\cos\gamma_3+\\ +\beta_x\varpi_x(\cos\gamma_1)\omega_y(\cos\gamma_3)M]\omega_z(\cos\gamma_2),\end{aligned}\quad(7)$$

s-polarization of the incident wave:

$$c^{+}=c_0\cdot\beta_y\omega_x(\cos\gamma_1)\varpi_y(\cos\gamma_3)\omega_z(\cos\gamma_2)\cdot\frac{1}{M}\cos\gamma_2;\quad(8)$$

c) for Z-position (Fig.1, d) and for the p-polarization of the incident wave:

$$\begin{aligned}c^{+}=c_0\cdot[\beta_y\omega_x(\cos\gamma_1)\varpi_y(\cos\gamma_2)\cos\gamma_1-\\ -\beta_x\varpi_x(\cos\gamma_1)\omega_y(\cos\gamma_2)\cos\gamma_2]\omega_z(\cos\gamma_3)\cdot\frac{1}{M}\cos\gamma_3,\end{aligned}\quad(9)$$

s-polarization of the incident wave:

$$\begin{aligned}c^{+}=-c_0\cdot[\beta_y\omega_x(\cos\gamma_1)\varpi_y(\cos\gamma_2)\cos\gamma_2+\\ +\beta_x\varpi_x(\cos\gamma_1)\omega_y(\cos\gamma_2)\cos\gamma_1]\omega_z(\cos\gamma_3)\cdot\frac{1}{M},\end{aligned}\quad(10)$$

where

$$M=\sqrt{\cos^2\gamma_1+\cos^2\gamma_2};$$

$$c_0=\frac{1}{2}(\varepsilon_{1r}-1)h_1E_0^{*}\frac{k_0^2}{(\beta_x^2+\beta_y^2)}a_0b_0L;\quad\varepsilon_{1r}=\frac{\varepsilon_1}{\varepsilon_0};$$

$$\omega_v(n)=\frac{1}{p_v^2-(q_vn)^2}\times\\ \times\begin{pmatrix}-i[p_v\cos p_v\sin(q_vn)-q_vn\sin p_v\cos(q_vn)]\\ [p_v\sin p_v\cos(q_vn)-q_vn\cos p_v\sin(q_vn)]\end{pmatrix};$$

$$\varpi_v(n)=\frac{1}{p_v^2-(q_vn)^2}\times\\ \times\begin{pmatrix}[p_v\sin p_v\cos(q_vn)-q_vn\cos p_v\sin(q_vn)]\\ i[p_v\cos p_v\sin(q_vn)-q_vn\sin p_v\cos(q_vn)]\end{pmatrix},$$

$$(v=x,y,z).$$

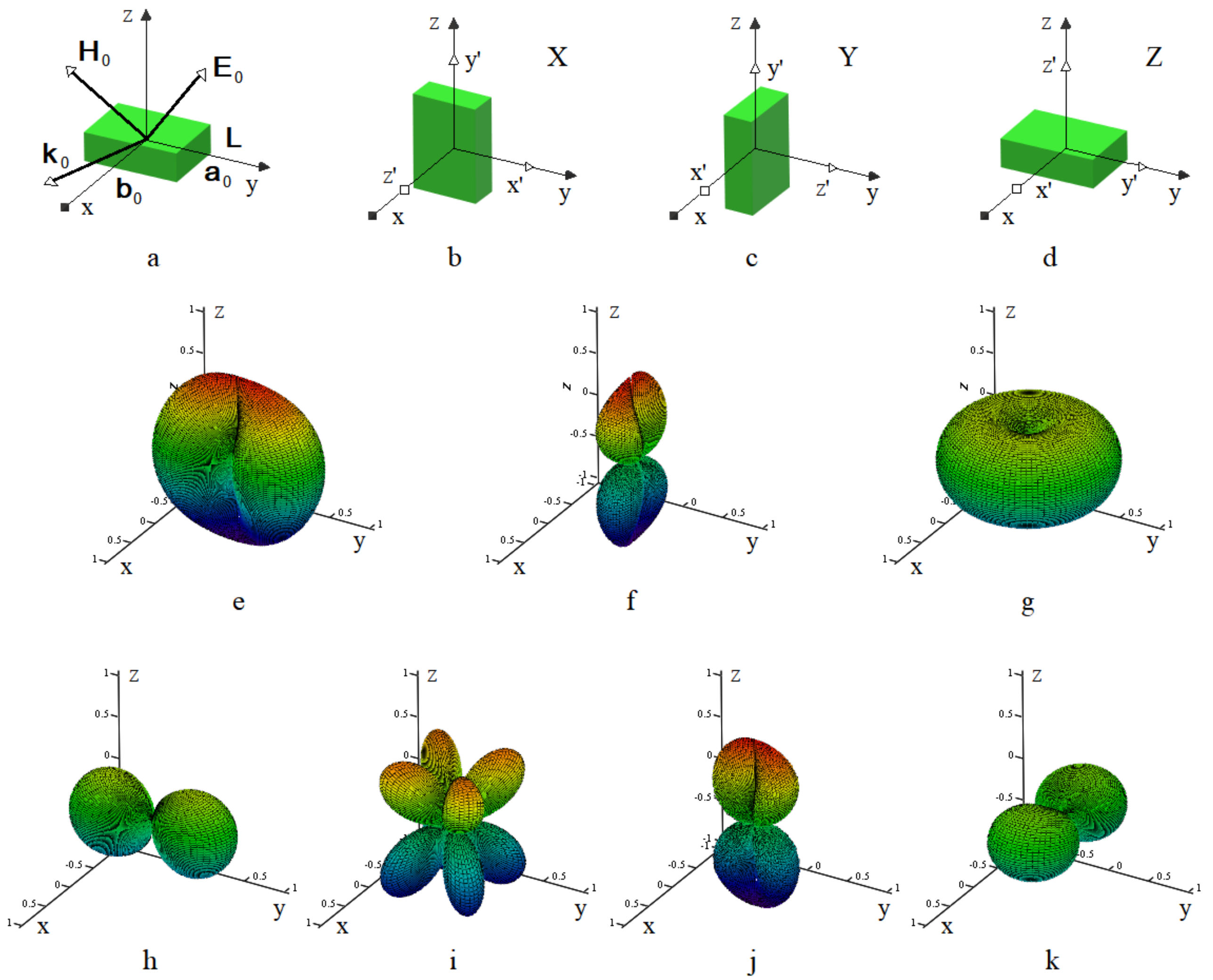

Fig. 1. $\vec{E}_0, \vec{H}_0, \vec{k}_0 = \vec{E}_0 \times \vec{H}_0$ unit vectors of the incident plain wave in the coordinate system of the lattice (x, y, z) (a). Three orthogonal orientations of a rectangular DR: X (b); Y (c); Z (d) relative coordinate system (x, y, z). Module $|c^+(\vartheta, \varphi)|$ in a spherical coordinate system for three orientations of the DR with H_{ccc} oscillation relative to the lattice coordinate system X (e, f); Z (g) for p-scattering (e); for s-scattering (f, g); of the DR with H_{scc} oscillation relative to the coordinate system X (h, i); Z (j, k) for p-scattering (h, j); for s-scattering (i, k)

C-functions (5–10) determine the degree of excitation of a DR by an incident plane wave in open space. The phase function is determined by the coordinates of the t-th DR center (x_t, y_t, z_t) in a lattice:

$$c_t^+ = c^+ e^{ik_0(x_t \cos\gamma_1 + y_t \cos\gamma_2 + z_t \cos\gamma_3)}. \quad (11)$$

Fig. 1, e-k shows the angular dependence of the modulus c-functions for scattering of p-type (e, h, j), s-type (f, g, i, k). Dependencies (e, h, i) in Fig. 1, correspond to the X-orientation shown in Fig. 1 (b), and (g, j, k), correspond to Z-orientation (d). The lowest frequency oscillation type H_{ccc} corresponds to (2) with $h_z = h_1 \cos\beta_x x' \cos\beta_y y' \cos\beta_z z$; next frequency oscillation type H_{scc} corresponds to (2) with $h_z = h_1 \sin\beta_x x' \cos\beta_y y' \cos\beta_z z'$. The relative dielectric constant of the resonator $\varepsilon_{1r} = 36$; relative sizes $b_0/a_0 = 1$; $L/a_0 = 0,4$.

The given dependences make it possible to determine the degree of interaction of the isolated DR with a plane wave, depending on the direction of its propagation. For example, in the case of p-polarization (Fig. 1, e), it is seen that there are no oscillations in the DR in the plane $\varphi = 0, \pi$, and in the case of s-polarization (Fig. 1, f) at $\varphi = 1/2\pi, 3/2\pi$.

3 Calculating scattering of electromagnetic waves by Plain Lattice of Rectangular DRs

The eigenoscillation electromagnetic field of the lattice of N coupled DRs we represented as a superposition of isolated fields of the resonators on the frequency

ω_0 of the lowest H_{ccc} mode:

$$\vec{e}^{\,s} = \sum_{n=1}^{N} b_n^s \vec{e}_n; \quad \vec{h}^s = \sum_{n=1}^{N} b_n^s \vec{h}_n. \tag{12}$$

The amplitudes b_n^s and frequencies ω_s of coupled DRs obtained from [8]. Representation (12) we used for solving the scattering problem of the wave $(\vec{E}^+, \vec{H}^+)$ on a lattice:

$$\vec{E} \approx \vec{E}^+ + \sum_{s=1}^{N} a^s \vec{e}^{\,s}; \quad \vec{H} \approx \vec{H}^+ + \sum_{s=1}^{N} a^s \vec{h}^s, \tag{13}$$

where the unknown amplitudes a^s $(s=1,2,\dots,N)$ are found from the relations [8] with considering (5–11). In this case, the coupling coefficients of rectangular resonators were calculated using the formulas [2].

The scattering electromagnetic field of the lattice (13) in the wave zone in the direction towards the observation point (θ,φ) represented as:

$$\vec{E}(\theta,\varphi) - \vec{E}^+(\theta_\pi,\varphi_\pi) = \vec{e}_0 f\langle\theta_\pi,\varphi_\pi|\theta,\varphi\rangle E_0 \frac{e^{-ik_0 r}}{k_0 r}. \tag{14}$$

Here $\vec{e}_0 = \vec{e}_0(\theta_\pi,\varphi_\pi|\theta,\varphi)$ – is the unit vector, defining the polarization of the scattered electric field in the wave-zone; $(\vartheta_\pi,\varphi_\pi)$ – is the fall wave direction; $f\langle\theta_\pi,\varphi_\pi|\theta,\varphi\rangle$ is the scattering amplitude.

Fig. 2, b, d illustrates the angular dependences of the squared modulus of the scattering amplitude for a plane p-type wave (b); s-type (d) on a square lattice (a) of 10×10 DR, (c), respectively. The dots conventionally show the centers of the resonators. The straight line shows the direction of propagation of the incident wave $\vec{k}_0$. The relative distance between the centers of adjacent resonators is $\lambda_0/4$ (λ_0 is the wavelength in free space at the frequency of H_{ccc} resonant oscillations ω_0). As can be seen from the above data, petal 1 (Fig. 2, b) is directed at an angle of "reflection" to the surface of the grating. Petal 2 is directed along the vector $\vec{k}_0$, whence, taking into account (14), it defines the lattice "shadow" resulting from reflection [17]. Both petals are located in the plane of incidence.

4 Calculating scattering of electromagnetic waves by Plain Lattice of Cubic shape DRs

The sketch of coupled Cubic DRs ($a_0=b_0=L$) lattice is shown in Fig. 3, a. In this case, in each resonator at the lowest frequency, three eigenoscillations of the H_{ccc} magnetic type can be simultaneously excited, differing from each other by rotation by angles of $\pi/2$.

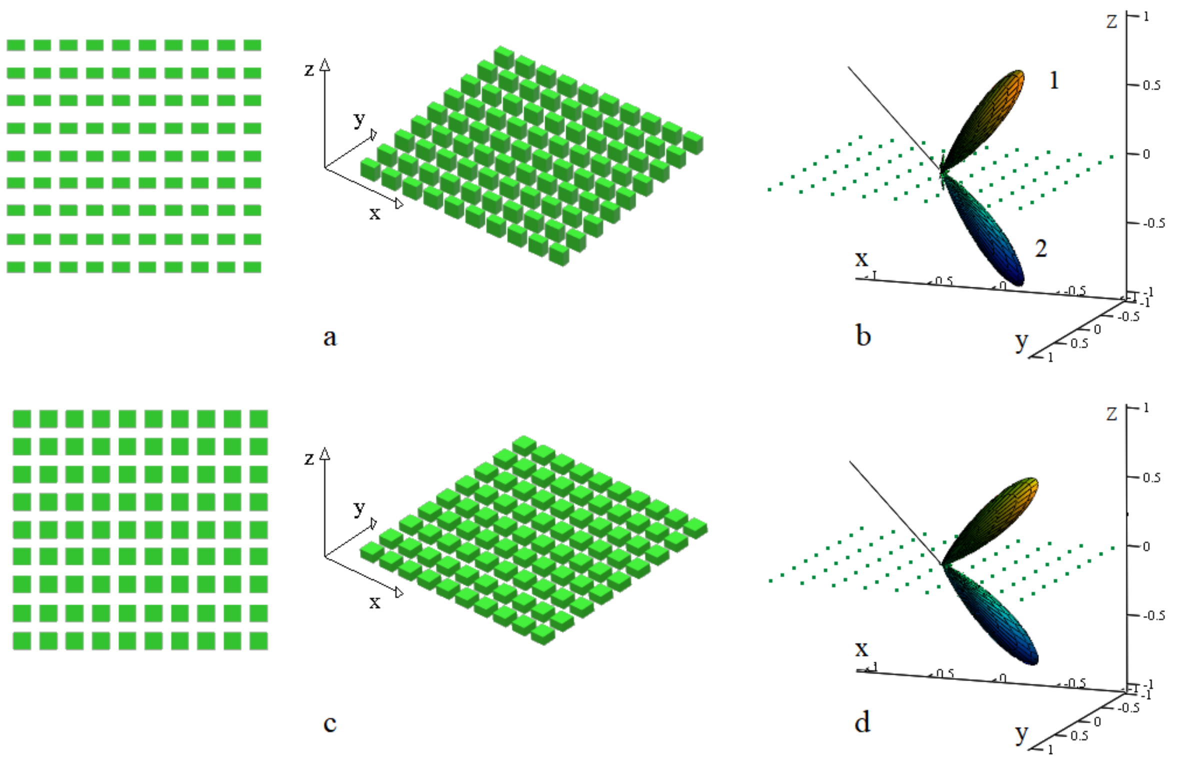

Fig. 2. Square lattice of rectangular DRs in position Y (a); in position Z (c). Characteristics of the scattering $|f\langle\theta_\pi,\varphi_\pi|\theta,\varphi\rangle|^2$ of a plane wave on a lattice (a) - (b); (c) - (d). Fall wave direction $\vartheta_\pi = 3/4\pi$; $\varphi_\pi = 0$

All these degenerate oscillations of the DRs are coupled to each other. This means that all $3N$ oscillations must be taken into account in the calculation (12–13). Fig. 3, b, c shows the result of calculating the angular scattering characteristics for a 10×10 cubic DR lattice.

An increase in the number of coupled degenerate oscillations of different "polarizations" leads to expansion and the appearance of additional lobes (Fig. 3, b). Additionally in some cases, frequency variation can lead to a noticeable rearrangement of the scattered electromagnetic field.

Discussion and Conclusion

In this paper, we propose model of scattering of plane electromagnetic waves by gratings of rectangular DRs in open space. The proposed model makes it much easier and faster to analyze the electromagnetic properties of complex structures of coupled DRs in open space. Unlike other analytical methods, the proposed model makes it possible to calculate all physically significant parameters of the structure with less computer time.

The performed calculations demonstrates the retention of the basic properties established for lattices of rectangulare resonators with the main magnetic types of oscillations [17].

Calculation of the spatial distribution of the values of the c-functions also makes it possible to determine the directions of the most significant interaction of the incident waves with the resonators of the array. This is especially useful in cases of higher types of oscillations, when the distribution of the DR electromagnetic field has a complex spatial structure.

As follows from our calculations, lattices made using a cubic DR are of considerable theoretical and practical interest. The indicated lattices, along with the indicated drawbacks, have a more rarefied frequency spectrum and, moreover, a lower polarization dependence.

The proposed theory can be used to calculate and analyze complex antenna structures, various dividers, multiplexers, and other communication devices in the microwave, infrared and optical wavelength ranges.

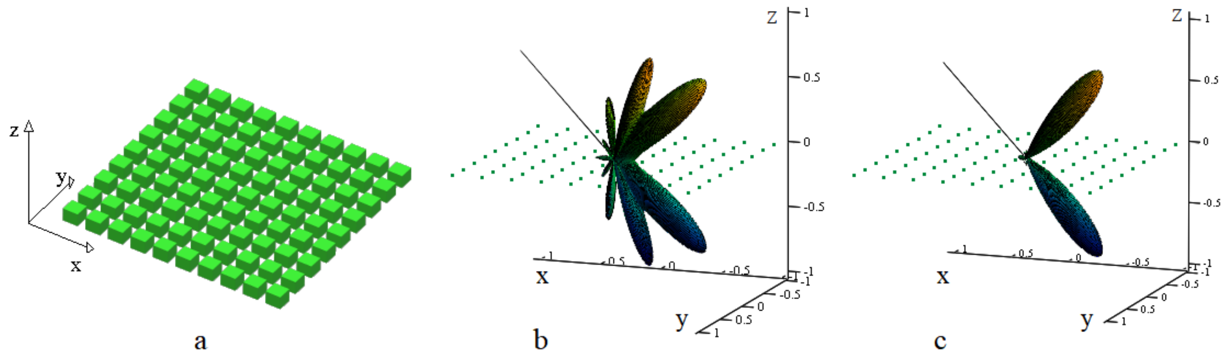

Fig. 3. A square lattice of a cubic shape DRs (a). Characteristic of the scattering of a plane wave of the p-type (b), s-type on the lattice (c) with degenerate oscillations of the DRs ($\vartheta_\pi = 3/4\pi$; $\varphi_\pi = 0$)

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Розсіювання електромагнітних хвиль на решітках прямокутних діелектричних резонаторів

Трубін О. О.

Розраховані і досліджені c-функції, що визначають ступінь впливу зовнішнього збуджуючого електромагнітного поля на прямокутний діелектричний резонатор (ДР) у відкритому просторі. Показано наявність напрямків з "нульовою" проекцією поля збудження на поле ДР. За допомогою теорії збурень, вивчено просторовий розподіл полів розсіювання, що виникає при падінні плоскої електромагнітної хвилі p- або s-типу, на квадратну решітку прямокутних діелектричних резонаторів. Побудована електродинамічна модель розсіювання на решітці ДР прямокутної форми. Продемонстровано появу відбитої і тіньової пелюстки при розсіянні на решітці прямокутних ДР з основними магнітними видами коливань. Досліджуються особливості розсіювання на решітці кубічної форми з виродженими магнітними коливаннями основного типу. Показано, що виродження власних коливань резонаторів призводить до більш складної картині розсіювання: появи додаткових пелюсток, а також зміни їх форми. Відзначено, що форма просторового розподілу розсіяного поля решітки може помітно змінюватися з варіацією частоти в межах смуги частот зв'язаних коливань резонаторів решітки. Отримані практичні результати моделювання дозволяють значно скоротити час обчислень і оптимізувати складні багаторезонаторні структури мікрохвильових та оптичних систем зв'язку, які одночасно виконують функції поділу або об'єднання каналів.

Ключові слова: розсіювання; решітка; прямокутний діелектричний резонатор; моделювання; c-функція; амплітуда розсіювання

Рассеяние электромагнитных волн на решетках прямоугольных диэлектрических резонаторов

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Рассчитаны и исследованы c-функции, определяющие степень воздействия внешнего возбуждающего электромагнитного поля на прямоугольный диэлектрический резонатор (ДР) в открытом пространстве. Показано наличие направлений с "нулевой" проекцией возбуждающего поля на поле ДР. С помощью теории возмущений, изучено пространственное распределение полей рассеяния, возникающее при падении плоской электромагнитной волны p- или s-типа, на квадратную решетку прямоугольных диэлектрических резонаторов. Построена электродинамическая модель рассеяния на решетке ДР прямоугольной формы. Продемонстрировано появление отраженного и теневого лепестка при рассеянии на решетке прямоугольных ДР с основными магнитными типами колебаний. Исследуются особенности рассеяния на решетке кубической формы с вырожденными магнитными колебаниями основного типа. Показано, что вырождение собственных колебаний резонаторов приводит к более сложной картине рассеяния: появлению дополнительных лепестков, а также изменению их формы. Отмечено, что форма пространственного распределения рассеянного поля решетки может заметно меняться с вариацией частоты в пределах полосы частот связанных колебаний резонаторов решетки. Полученные практические результаты моделирования позволяют значительно сократить время вычислений и оптимизировать сложные многорезонаторные структуры микроволновых и оптических систем связи, одновременно выполняющие функции разделения или объединения каналов.

Ключевые слова: рассеяние; решетка; прямоугольный диэлектрический резонатор; моделирование; c-функция; амплитуда рассеяния