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On the Absorption of Electromagnetic Waves by a Linear Lattice of Electric Currents and their Reaction Forces

Vladimir Arabadzhi

Institute of Applied Physics, Nizhny Novgorod, 603951, Ulianov st. 46, Russia.

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***Corresponding author:** Vladimir Arabadzhi, Institute of Applied Physics, Nizhny Novgorod, 603951, Ulianov st. 46, Russia.

Abstract

We consider a quarter-wave linear lattice of electric currents (Hertzian dipoles) that absorbs power from an incident wave proportional to the square of the number of currents and square of wavelength, independent or the lattice's geometric dimensions. It was found out numerically that the phase structure of optimal absorption currents exhibits binary alternating values with spatial periodicity. The corresponding constant in time Ampere forces are also estimated: (a) the total force with which the incident wave acts on the all currents and (b) the total force of interaction between the currents. These two total forces mutually compensate each other. Analogous problems are considered also for one-dimensional actively absorbing Huygens source and the case of dissipative passive bulk absorption are considered too.

Keywords

Absorption cross-section; Ampere forces; given currents; active absorption; collective resonance; forces of wave reaction; Huygens source; passive absorption; dissipative bulk absorption

1. Introduction

Numerous works [1-7] have been devoted to the regime of maximum absorption of the incident wave and the wave field reaction forces on antennas of small wave sizes, as well as to combinations of multiple small antennas in the form of metamaterials. Also constant in time forces of wave field reaction on small antennas have been considered [8-11]. Next, we will characterize the absorption properties of the currents by its absorption cross-section (including the maximum possible cross-section). The absorption cross-section, denoted below, is defined as the ratio of the time-averaged power absorbed by the antenna to the time-averaged power flux density of the incident wave. It is known ([1], [2], [4]) that an antenna (acoustic monopole, Hertzian electric dipole) of arbitrarily small wave-dimensions can have an absorption cross-section of the order square of the incident wavelength $\sim\lambda_0^2$. In this paper it will be shown that a linear antenna array of N Hertzian dipoles (or acoustic monopoles [15], [16]) has an absorption cross-section $\sim N^2$ at arbitrarily small wave dimensions of the array. Below we will consider the absorption characteristics of an spatially periodic linear array of external currents, as well as the forces (constant in time) of action of incident wave on the array currents from the incident wave side and the forces with which these currents acting on each other. Заметим, что это не пондеромоторные силы [12], с которыми электрическое поле с пространственно неоднородной интенсивностью действует на заряженные частицы независимо от знака их заряда. Note that these are not ponderomotive forces [12], with which an wave electric field with spatially non-uniform intensity acts on charged particles regardless of the sign of their charge. This article examines the interaction forces of spatially fixed electric currents through the magnetic field they create, i.e. classical Ampere forces [13]. The idealization used below is the assumption that we have the means to create external currents, and these means (like the external currents) are transparent, do not distort the wave incident and do not depend on it. It is easy to see that the characteristics of the external current differ significantly from those of the well-known metal vibrator [14]. However, despite the idealizations adopted in the formulation of the problem, the obtained conclusions are of some interest for understanding the process of absorption of long waves by small antennas [5].

2. Incident Wave Absorption by a Single Electric Current

We call the absorption the case when the incident wave electric field $\boldsymbol{E}_0\, exp(\,i\,\omega_0\,t - i\,k_0\,x)$ (ω_0–frequency, $k_0 = \omega_0/c_0 = 2\pi\lambda_0$–wavenumber, λ_0–wavelength, $c_0 = 1/\sqrt{\mu_0\varepsilon_0}$ wave speed, ε_0,μ_0–electric and magnetic constants) makes nonzero work $\sim(1/2)\,Re\{\boldsymbol{J}(1) * \boldsymbol{E}_0\ell_0\} > 0$ on the stated current $\boldsymbol{J}(1)||\boldsymbol{E}_0||\boldsymbol{z}_0$ of length $\ell_0 << \lambda_0$ averaged on the period $T_0 = 2\pi\ \ /\omega_0$ of an incident wave (Fig. 1,a). Note that even with maximum absorption, the total field (incident wave plus the wave emitted by the current) can never become zero (except in the spatially one-dimensional case). Let us consider one linear cylindrical given external current (Hertz dipole) with complex amplitude $J(1)$, length $\ell_0 << 2\pi\ \ c_0/\omega_0 = \lambda_0$ and diameter $a_0 << \ell_0$, uniform in length and monochromatically oscillating in time at frequency ω_0 ($\boldsymbol{z}_0$,$\boldsymbol{y}_0$,$\boldsymbol{x}_0$—the unit vectors of the Cartesian coordinate system, Fig. 1a). The external current is electrostatically neutral, i.e., the total charge density in the external current is zero. A linearly polarized plane wave with electric field $\boldsymbol{E}_0\, exp(\,i\,\omega_0\,t - i\,k_0\,x)$ propagating from left to right is incident on the current $\boldsymbol{J}(1) \uparrow\uparrow \boldsymbol{E}_0||\boldsymbol{z}_0$. It is important that external electromagnetic fields do not affect the speed of charge movement in the given current, which, therefore, does not scatter the incident waves. As is known [1], [4], the maximum absorption cross-section of a Hertzian dipole is

$$\sigma(1) =< W_{\mathrm{A}}(1) >_{\max} / < W_0 >= 3\lambda_0^2 / 4\pi$$

where $< W_0 >= \left|E_0\right|^2 / 2\hat{\mathrm{Z}}(0)$—time-average (denoted by < >) power flux density of the incident wave,

$$< W_{\mathrm{A}}(1) >= \left|E_0\right|^2 \mathrm{l}_0^2 / 8\ \ \hat{\mathrm{Z}}(1) \tag{1}$$

is the maximum time-average power extracted by a single current (or a device supporting this current) from the incident wave or the maximum work per unit of time performed by the field of the incident wave on the current $\boldsymbol{J}(1)$).
$\mathrm{Re}\,\hat{Z}(1) = \hat{Z}(0)\mathrm{l}_0^2 k_0^2 / 6\pi$ —radiation resistance of one current [13], $\hat{Z}(0) = \sqrt{\mu_0/\varepsilon_0}$—impedance of a plane linearly polarized wave in a vacuum. The maximum value (1) of the absorption cross-section is provided by the current

$$\mathbf{J}_0(1) = (1/2)[\mathrm{Re}\,\hat{Z}(1)]^{-1}\mathbf{E}_0\mathrm{l}_0 \tag{2}$$

The magnetic field of the incident wave acts on the current with an Ampere force

$$\mathbf{F}_0(1) = \mu_0\mathrm{l}_0[\mathbf{J}_0(1) \times \mathbf{H}_0], \tag{3}$$

i.e. $\boldsymbol{F}_0(1) \uparrow\uparrow \boldsymbol{k}_0 = \boldsymbol{x}_0 k_0 = \boldsymbol{x}_0 2\pi/\lambda_0$ the wave repels the absorbing current (strictly speaking, force (3) acts on certain “guides” that do not affect the field). The spectral power of the force and the absorbed power are concentrated at frequencies $\omega = 2\omega_0$ and $\omega = 0$. The time-averaged (at frequency $\omega = 0$) maximum absorbed power $< W_A$ and force $< \mathrm{F}_0(1) >$ are related by the relation:

$$< F_0(1) >_{\max} =< W_{\mathrm{A}}(1) >_{\max} / c_0\,. \tag{4}$$

Note that the constant force of “repulsion” of a single current by an incident wave does not depend on the length ℓ_0 of the current (just like $< W_{\mathrm{A}}(1) >_{\max}$) and is different from zero, despite the symmetry (with respect to "x") of the radiation pattern of a single current.

3. Absorption and Reaction Strenhth as Functions of Numbers of Lattice Elements

At points $x = \boldsymbol{X}(N) = \{0,\ \ \varDelta,\ \ 2\varDelta,\ \ \ldots,\ \ N\,\varDelta\}$ on $[0, L_0]$ the axis "x"segment $[0, L_0]$ (Figs. 1a,b) with a period

$\Delta = L_0/(N-1)$, there are $N > 1$ linear currents $\mathbf{J} = \{J_1, J_2, ..., J_N\}\mathbf{z}_0$ of equal length $\ell_0 << \Delta < \lambda_0$ with complex amplitudes J_n oriented along the axis "z". Thus, we have defined a lattice of extraneous currents $\boldsymbol{J}$. Along the axis "x" from left to right, the incident wave described above propagates with electric and magnetic fields

$$\boldsymbol{E}_0 = \boldsymbol{\Psi}(N)\, E_0 \boldsymbol{z}_0\, exp(i\,\omega_0\, t)\ ,\ \boldsymbol{H}_0 = \boldsymbol{\Psi}(N)\, H_0 \boldsymbol{y}_0\, exp(i\,\omega_0\, t), \tag{5}$$

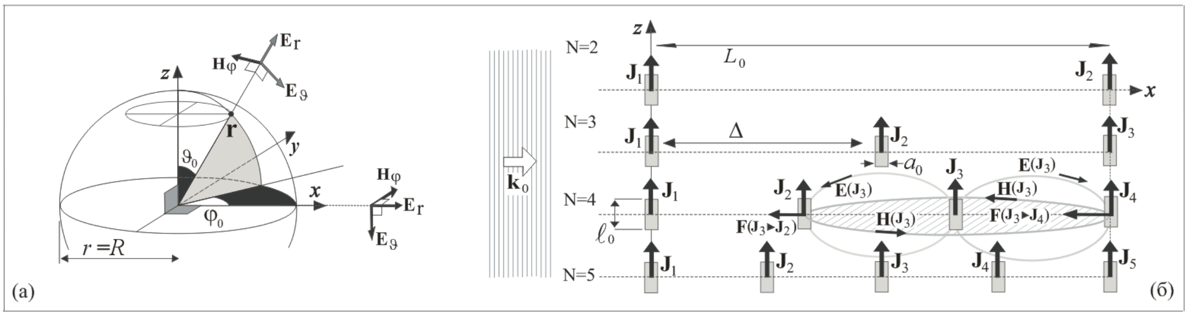

Figure 1. Geometry of the 3D problem for the current grid.

(a) components of the electromagnetic field of the current (Hertzian dipole) located at the center of the Cartesian and spherical coordinate systems; (b) the structure $J_0(N) = \{J_1, J_2, \ldots, J_N$ of the current grid for different numbers N of currents, as well as the grid parameters: L_0—total length, Δ—spatial period of the grid, a_0—current diameter, ℓ_0— length of current.

where the vector $\boldsymbol{\Psi}(N) = \{1, exp(-i\,\Delta), exp(-2\,i\,\Delta), \ldots, exp(-Ni\,\Delta)\}$ represents the phases of the fields at points $\boldsymbol{X}(N)$, E_0 and H_0 the complex amplitudes of the fields at point $x = 0$, and $E_0/H_0 = \hat{Z}(0)$. Note that the vector $\boldsymbol{\Psi}(N)$ describes the lattice dimension, while the vectors, $\boldsymbol{z}_0$, $\boldsymbol{y}_0$– the directions of the fields $\boldsymbol{E}_0$ and $\boldsymbol{H}_0$, i.e., the vectors $\boldsymbol{\Psi}(N)$ and $\boldsymbol{z}_0$, $\boldsymbol{y}_0$, belong to different spaces. If we (in the absence of other currents and an incident wave) define a current $J_m \mathbf{z}_0$ $(m = 1,2,3, \ldots, N)$ of length ℓ_0 at point $x_m = (m-1)\Delta$ then at point $x_n = (n-1)\Delta \neq x_m$ (at the location of the current J_n, $n \neq m$) we obtain an electric field $E_m \mathbf{z}_0 = Z_{mn} J_m \mathbf{z}_0$ or potential difference $\ell_0 Z_{mn} J_m$. Here Z_{mn}–are the elements of the impedance matrix of the current lattice, determined by known expressions for the Hertzian dipole field [13]. Moreover, the real parts of the diagonal elements $\mathrm{Re}\, Z_{nn} = \mathrm{Re}\, Z(1)$ are the known radiation resistances of each Hertzian dipole in the absence of other dipoles (currents) and an incident wave (see Section 1). Now, using the impedance matrix $\widehat{\boldsymbol{Z}}(N)$, we write down the total time-averaged power absorbed by all its $N > 1$ lattice currents:

$$< W_A(\mathrm{N}) >= (1/2)\,\mathrm{Re}\left\{\left[(\mathbf{E}_0)^{*\mathrm{T}} \ell_0 - \hat{\mathbf{Z}}(\mathrm{N})\mathbf{J}\right]\ \mathbf{J}^{*\mathrm{T}}\right\}, \tag{6}$$

where $(< W_A(\mathrm{N}) >) > 0$ denotes the absorption of the incident wave energy, and $(< W_A(\mathrm{N}) >) < 0$ is the grating radiation. In (6) $\hat{\mathbf{Z}}(\mathrm{N}) = \{\hat{Z}_{\mathrm{n,m}}\}$ is the square impedance matrix of the grating. The element $\hat{Z}_{\mathrm{n,m}} J_{\mathrm{m}}$ represents the electric field

$$E_\theta = (\mathrm{i}\, k_0 J_{\mathrm{m}} \ell_0 Z(0)/4\pi)\ (\sin\theta)\ r_{\mathrm{nm}}^{-1} \exp(-\mathrm{i}\, k_0 r_{\mathrm{mn}})\ [1 + (\mathrm{i}\, k_0 r_{\mathrm{mn}})^{-1} + (\mathrm{i}\, k_0 r_{\mathrm{mn}})^{-2}], \tag{7}$$

created by the current J_m at the element with the number "$n \neq m$" ($\theta = \pi/2$, r_{mn} is the distance between the elements "m" and "n"), when all other currents J_n with the numbers "$n \neq m$" are zero. The real and imaginary parts of the matrix $\widehat{\boldsymbol{Z}}(N)$ are symmetrical: $\mathrm{Re}(\hat{Z}_{\mathrm{n,m}}) = \mathrm{Re}(\hat{Z}_{\mathrm{m,n}})$, $\mathrm{Im}(\hat{Z}_{\mathrm{n,m}}) = \mathrm{Im}(\hat{Z}_{\mathrm{m,n}})$. By analogy with the above-described one-dimensional (one current) case, we will search for the current vector that provides the maximum $< W_A(\mathrm{N}) >$, in the form (as in [15, 16])

$$\mathbf{J}(\mathrm{N}) = \gamma[(\mathrm{Re}\,\hat{\mathbf{Z}}(\mathrm{N})]^{-1} \mathbf{E}_0 \ell_0 \tag{8}$$

where γ is a real coefficient. Substituting (8) into (6), it is easy to verify that: (a) at $\gamma = 0$ and $\gamma = 1 < W_A$ (i.e., there is no energy exchange between the lattice and space); (b) at $\gamma > 1$ (or $\gamma < 0$) the lattice radiates; (c) at $0 <$

$\gamma < 1$ the lattice absorbs, and at $\gamma = 1/2$ absorbs the maximum power (see the family of parabolas corresponding to different numbers N of lattice currents in Fig. 2a):

$$< W_A(N) >_{\gamma=1/2} = < W_A(N) >_{max} = (l_0^2/8)\,\mathrm{Re}\{\mathbf{E}_0^{*T}[(\mathrm{Re}\,\hat{\mathbf{Z}}(N)]^{-1}\mathbf{E}_0\}\,, \quad (9)$$

or $< W_A(N) >_{max} = (1/8)\,\mathrm{Re}\{\mathbf{J}_0^{*T}(N)[(\mathrm{Re}\,\hat{\mathbf{Z}}(N)]\ \mathbf{J}_0(N)\}$. Further, we will consider only the current

$$\mathbf{J}_0(N) = (1/2)[(\mathrm{Re}\,\hat{\mathbf{Z}}(N)]^{-1}\mathbf{E}_0 l_0\,, \quad (10)$$

which, along with absorption, also radiates a field of the same (as absorbed) power (9) in the absence of an incident wave. Taking into account the well-known expression (7) for the electromagnetic field of a Hertzian dipole [4], we obtain the following expression for the off-diagonal element

$$\mathrm{Re}(\hat{Z}_{n,m}) = \mathrm{Re}(E_m l_0 / J_n) = -(k_0 l_0\,\hat{Z}(0)/4\pi)\ \ \mathrm{Re}\{\exp(-S_{m,n})\ [(S_{m,n})^{-1} + (S_{m,n})^{-2} + (S_{m,n})^{-3}]\} \quad (11)$$

(where $S_{m,n} = i\,k_0\Delta|n-m|$) is a matrix $Re(\widehat{\boldsymbol{Z}}(N))$ with identical diagonal elements $\mathrm{Re}(\hat{Z}_{n,n}) = \hat{Z}(0) l_0^2 k_0^2/6\pi$ $(1 \le n \le N)$.

Using normalization, we obtain simpler dimensionless expressions for the maximum collectively absorbed power (normalized to (1)) and for the total averaged in time Ampere force $< \boldsymbol{F}_0(N) > = (\mu_0\ell_0/2)\,Re[\boldsymbol{J}_0(N) \times \boldsymbol{H}_0^*]$ of the magnetic field of the incident wave on the grid with currents (10), normalized to the time-averaged force (3) acting on a single current of maximum absorbing (2). The dependence of both quantities $< W_A(N) >_{max} / < W_A(1) >_{max}$ and $< F_0(N) > / < F_0(1) >$ on the number of currents is determined by one dimensionless function $\Theta(N) \sim N^2$ (Fig. 2b), i.e.

$$\frac{< W_A(N) >_{max}}{< W_A(1) >_{max}} = \frac{< F_0(N) >}{< F_0(1) >} = \Theta(N) \approx (3/4)\,N^2 \quad (12)$$

where $$\Theta(N) = \mathrm{Re}\left\{\boldsymbol{\Psi}_0(N)\left(\begin{bmatrix} 1 & A_{m,n} \\ A_{n,m} & 1 \end{bmatrix}^{-1} \boldsymbol{\Psi}_0(N)\right)^{*T}\right\}. \quad (13)$$

It should be noted that final analytical form $\approx (3/4)\,N^2$ (12) was obtained exclusively by a numerical (not analytical) method (analogously to [15], [16]). The off-diagonal elements of the matrix in (13) are equal to,

and all diagonal elements are equal to 1. The difference between the functions (12), (13) and the acoustic analogue described in [15, 16] is due to the additional powers of $(S_{m,n})^{-2}$ and $(S_{m,n})^{-3}$ (which are not present in the analogous acoustic problem for monopoles) in the description of the near current field. When calculating using formula (12), we operate with numbers $\sim 10^{19}$, which makes it difficult to find $\Theta$and sharply increases the requirements for the accuracy of calculations at $N > 10$.

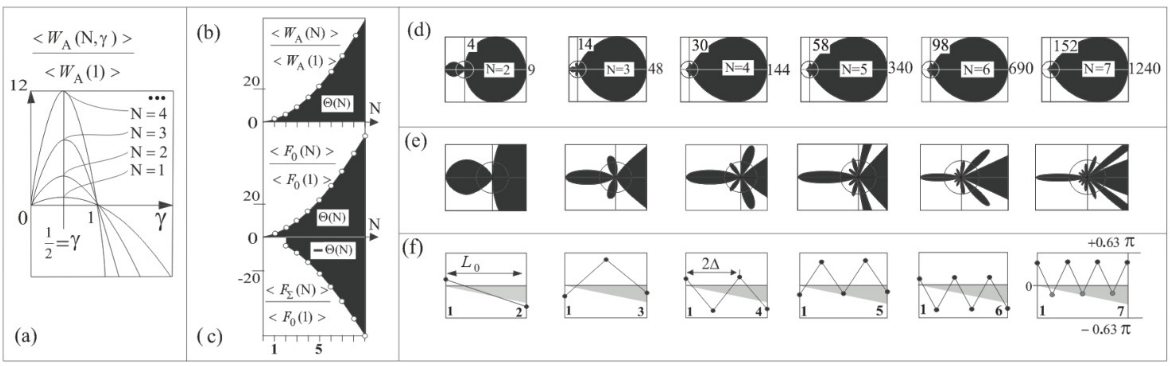

Figure 2. Characteristics of the 3D current grid in the maximum absorption mode depending on the number of its elements located on an interval with wave-dimension $k_0L_0 = \pi/2$.

(a) normalized time-average power (6) absorbed by the $N = 1 \div 4$ current of grid (8) depending on the coefficient ; (b) normalized average power absorbed by of the grid with currents (10); (c) normalized average force of action of the incident wave (upper graph) on the current grid (10) and normalized total force of action of the radiating currents (10) on each other in the absence of the incident wave (lower graph); (d) cross-section "x, y" of the directivity diagram of the power flow radiated by the current grid. The numbers indicate the normalization scales of the main lobe of the radiation pattern; (e) the fine structure of the lobes of the radiation pattern cross-section "x, y" (side and back lobes) for different numbers of currents (10); (f) the phases of the currents (10) (points connected by a solid line) and the phase of the incident wave along the array (linear gray profile) in radians.

If the number of currents is $N > 1$, then in addition to the force (3) described above with which the incident wave acts on each of the currents (10), a total force (also the Ampere force) also arises with which each current acts on another current through the azimuthal component of the magnetic field it generates. At the same time, the radiation pattern of these currents becomes unidirectional (forward, along the path of the incident wave), and the reaction force of the interacting currents, on the contrary, "attracts" the grating to the incident wave, i.e. $< \boldsymbol{F}_\Sigma(N) > \uparrow\downarrow \boldsymbol{k}_0$. Thus, we consider a superposition of two problems: (a) the action of the incident wave on external currents; (b) the action of these same currents on each other (and their radiation) in the absence of the incident wave. In the latter case, the time-averaged, non-zero total force of the action of currents (10) on each other may seem to be a violation of Newton's 3rd law, if we do not take into account the connection of the lattice with infinite space through these currents radiation. The given currents (10) formed for the incident wave (5) in the absence of the incident wave create an anisotropic (along the axis "x") power flux density diagram similar to the Huygens source (see Fig. 2b) of radiation with the main lobe in the direction $\boldsymbol{k}_0$. Similarly to (3), we write the force of the current $\mathbf{J}_m(\mathrm{N})$ acting on the current $\mathbf{J}_n(\mathrm{N})$:

$$\mathbf{F}_{m,n}(\mathrm{N}) = \mu_0 l_0 [\mathbf{J}_n(\mathrm{N}) \times \mathbf{H}(\mathbf{J}_m(\mathrm{N}))], \tag{14}$$

through the field (see [14])

$$\mathbf{H}(\mathbf{J}_m(\mathrm{N})) = \mathbf{y}_0 \,\mathrm{sgn}(m-n)\; (k_0^2 l_0 J_m / 4\pi)\; [(S_{n,m})^{-1} + (S_{n,m})^{-2}]\; \exp(-S_{n,m}) \tag{15}$$

If we now sum the forces (14) and normalize them by the force (3) of a single current, we obtain (numerically) a dependence on the dimensionless time-averaged reaction force (in projection onto the axis "x")

$$< F_\Sigma(\mathrm{N}) > / < F_0(1) > = \sum_{n \neq m}^{N} < F_{n,m}(\mathrm{N}) > / < F_0(1) > \tag{16}$$

close to (12), but with the opposite sign. Thus, within the limits of calculation accuracy, we can assert that

$$< F_\Sigma(N) > + < F_0(N) > \;\approx 0 \tag{17}$$

at $N > 1$ (Fig. 2, c). Thus, the reaction force $< \boldsymbol{F}_\Sigma(N) > \downarrow\uparrow \boldsymbol{x}_0$ of the highly anisotropic forward radiation of the grating compensates for the force $< \boldsymbol{F}_0(N) > \uparrow\uparrow \boldsymbol{x}_0$ of the absorbed wave (in Section 4 this will also be demonstrated for a one-dimensional Huygens source in the incident wave absorption mode). In Fig. 2,f it is easy to notice the spatial periodicity (the period is equal to the period of the current placement) and the binarity of the phases (the phases take only two alternating values with opposite signs) of the currents intended for maximum absorption of the incident wave. Judging by Fig. 2, f, it is natural to assume that with an increase in the number of currents, their phase structure will be preserved.

4. Reaction Forces in Active and Passive Absorption in a One-Dimensional Problem

Fig. 3, a,b shows how electric and magnetic currents $\boldsymbol{J}_e$ and $\boldsymbol{J}e_m$ form together one-sided radiation with power flux density $\boldsymbol{W}_\Sigma = 0$ at $z < 0$ and $\boldsymbol{W}_\Sigma \neq 0$ at $z > 0$, i.e. orthogonal electric and magnetic dipoles on a plane are forming 1D Huygens source [17]. The forces of the field reaction to currents are presented in Fig. 3, c: the electric field $\boldsymbol{E}_e$ created by the current $\boldsymbol{J}_e$ acts by the Ampere force $\boldsymbol{F}_h$ on the magnetic current $\boldsymbol{J}_m$ and vice versa, the magnetic field $\boldsymbol{H}_m$ generated by the magnetic current $\boldsymbol{J}_m$ acts with the Ampere force $\boldsymbol{F}_e$ on the electric current $\boldsymbol{J}_e$. In this case, the total surface density of the reaction force of the Huygens source radiation $\boldsymbol{W}_{rad}$ power is equal to $< \mathbf{F}_1 > = - < \mathbf{W}_{rad} > / c_0$. On the other hand, with active compensation of the incident wave by the Huygens source field (Fig. 4, g), we obtain the force of action of the incident wave on the currents of the Huygens source emitting the compensating wave $< \mathbf{F}_2 > = < \mathbf{W}_{in} > / c_0$. Thus, the total force of the field reaction to the boundary S_0 with active compensation or complete active non-reflective absorption of the incident wave is equal to zero, i.e. $< \boldsymbol{F}_0 + \boldsymbol{F}_\Sigma > = 0$. Let us emphasize that above we considered the active absorption of the incident wave by *discrete spatially* *concentrated currents* $\boldsymbol{J}_e$ and $\boldsymbol{J}_m$, since the power flow lines of the incident wave *ended directly* on these flat currents. Simply put, the Huygens source (a plane with mutually perpendicular magnetic and electric surface currents) creates a field in the upper half-space (Fig. 3,c) that is co-travelling with the incident wave and opposite in sign, while in the lower half-space it adds nothing to the incident wave. This means that the power flow lines of the incident wave terminate on the plane of the Huygens source, which absorbs the energy of the incident wave.

Let us now consider the 1D problem of passive dissipative spatially continuously distributed (Fig. 3, d) reflectionless absorption of an incident plane linearly polarized wave, normally incident on a weakly conducting (i.e., when the condition $\chi/\varepsilon_0\omega_0 << 1$ of the bias current dominating the conduction current is met, where χ is the electrical conductivity of the medium) thick flat layer of thickness $\bar{L}_0$. The currents excited by an incident wave in a thick layer of a weakly conducting (this is the condition of non-reflective absorption) medium do not create an antiwave at the layer output that compensates for the original incident wave, since these are conduction currents (dependent on the field), and not specified currents, considered, for example, in Fig. 3a, b,c. The smallness of the amplitude modulus $|R|$ of the wave reflected from the layer is ensured by the condition $|T|{\sim}\delta/\bar{L}_0 << 1$, and the smallness of the amplitude modulus of the wave transmitted through the layer is guaranteed by the condition $|T|{\sim}\delta/\bar{L}_0 << 1$, where $\delta = \mathrm{c}_0/\sqrt{2\pi\chi\omega_0\mu_0}$ is the thickness of the skin layer. Note that above passive absorption acts simultaneously with the incident wave propagation in absorbing layer. With such a complete ($|R| + |T| << 1$) non-reflective passive absorption of the incident wave (in a weakly absorbing layer of thickness $\bar{L}_0$), the interaction between the currents can be neglected, i.e. ($|<\boldsymbol{F}_0>| >> |<\boldsymbol{F}_\Sigma>|$). In this case, the average over time density of the reaction force of the incident wave on the layer is determined by the expression $<\boldsymbol{F}>=<\boldsymbol{W}_0>/\mathrm{c}_0$, i.e. the incident wave repels the absorbing layer (absolutely inelastic impact of “photons” on the boundary $z = 0$). It is easy to show that this repulsion is 2 times weaker than the repulsion of a mirror-reflecting, ideally conducting surface (an absolutely elastic impact of “photons” on the boundary $z = 0$), which was demonstrated in the famous P.N. Lebedev’ experiment [8].

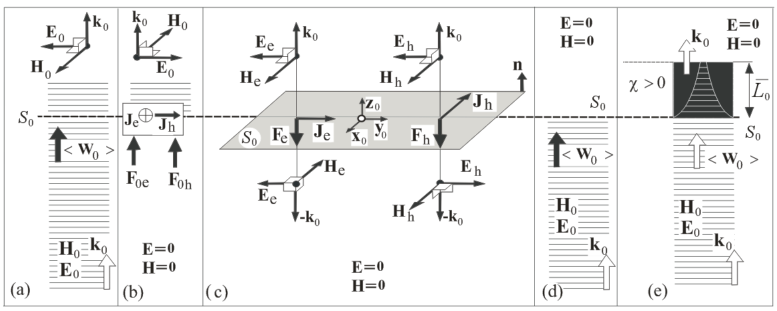

Figure 3. Reflectionless active absorption of an incident wave (by an Huygens source) and dissipative (by a weakly conducting thick layer) in a one-dimensional problem: (a) an incident plane linearly polarized wave with an average vector of power flux density $<\mathrm{W}_0>$, a wave vector k_0 and amplitudes of magnetic H_0 and electric E_0 fields; (b) electric J_e and magnetic J_h currents on a plane S_0 in the absence of an incident wave acting on them with forces $\mathrm{F}_{0\mathrm{e}}$ and $\mathrm{F}_{0\mathrm{h}}$, respectively; (c) electric E_e, E_h and magnetic H_e, H_h fields created by electric J_e and magnetic J_h currents, respectively, and the Ampere forces $\mathrm{F}_\mathrm{e} = -\mathrm{F}_{0\mathrm{e}}$ and $\mathrm{F}_\mathrm{h} = -\mathrm{F}_{0\mathrm{h}}$, with which the fields H_h and E_e act on the currents J_e, J_h in the absence of an incident wave; c) the total field created by the incident wave and currents J_e, J_h and (i.e. (a) + (b) = (d)) and the total force $\mathrm{F}_\mathrm{e} + \mathrm{F}_{0\mathrm{e}} = 0$ and $\mathrm{F}_\mathrm{h} + \mathrm{F}_{0\mathrm{h}} = 0$ acting on currents J_e and J_h; d) passive absorption of the incident wave (a) in a weakly conducting (weakly reflecting) thick (opaque) layer of thickness $\bar{L}_0$, when the incident wave simply acts on the conducting layer with an average force $<\mathrm{F}_0>=<\mathrm{W}_0>/c_0$.

5. Conclusions

The grating, considered geometrically, represents a quarter-wave spatial interval over which we equidistantly distribute an increasing number N of currents. The obtained distribution of electric currents in this grating is given such, providing an absorption cross-section proportional to the square N^2 of the number of its elements (currents). The incident wave is assumed to propagate along the array.

Near-field wave coupling between currents (off-diagonal elements of the impedance matrix) is involved in the energy absorption process by the antenna. Naturally, in the problem under consideration, the absorption diagrams of such an antenna are infinitely sharpened (narrowed) in the region of spatial frequencies (when scanning the direction of the incident wave) and in the region of temporal frequencies (when scanning the time frequency of the incident wave). At the same time, the requirements for the accuracy of the geometric and electrical implementation of the grating are increasing. While the mode of maximum absorption by a single current is often called the resonant absorption (2) mode [2], the above-described grating implements "collective resonance" (10) ([15], [16]).

It is shown that at $N = 1$, the incident wave "repels" the absorbing current (despite the symmetrical radiation pattern of the current), and at $N > 1$ (when the radiation pattern of the grating becomes unidirectional) the total force of the field reaction on the grating in the maximum absorption mode is zero. It was found that the phases of the vector currents (10), optimal for absorption, take only two (binary) different values with opposite signs and are spatially period 2Δ. Judging from Fig. 2f, it is natural to assume that as the number N of currents increases, their phase structure will be preserved.

Note that at large wave dimensions $k_0 L_0 >> 1$ of the grating, for a larger absorption cross-section, it is advisable to orient it (with the corresponding structure of the current vector (10)) across the path of the incident wave ($\mathbf{x}_0 \mathbf{k}_0 = 0$), and for a grating of small wave sizes $k_0 L_0 << 1$ (or, for example, a quarter-wave), for maximum absorption it must be oriented (with the corresponding structure of the vector (10)) along the propagation vector of the incident wave ($\mathbf{x}_0 \mathbf{k}_0 = k_0$).

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