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Linearly polarized field of a flat aperture

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Abstract – The article analyzes a flat circular aperture and proposes to use a new analytical expression that describes the radiation pattern of an elementary radiator of an antenna aperture depending on time and integration angle. The formula presented in the paper can be applied to any flat section of the aperture without taking into account its shape. A new equation for the antiderivative function of the impulse response of a circular aperture is presented in the form of an elliptic integral of the second kind. It is shown that the theoretically calculated results are in good agreement with numerical simulations. In the analysis of the numerical model, the method of finite integration in the time domain (FIT) was used. Due to the requirement of a large computational resource, the numerical model was simplified.

Keywords – aperture; EM wave; linear polarization; impulse response.

Introduction

Aperture antennas are widely used for various engineering solutions, primarily for satellite communications, e.g., parabolic emitters. The main advantage of such antennas is the high amplification gain, which is achieved because of the large ratio of the antenna size to the maximum wavelength of the signal used [1].

Although the fields of narrowband antennas were investigated and described 50–70 years ago, because of cumbersome calculations using monochromatic signals, several issues, such as the far-field criterion, are still debated. Uncertainties in the choice of such parameters for measuring the directional pattern in the near field, such as the aperture–probe distance and the size of the scanning area, also exist.

Electromagnetic fields of pulsed signals from aperture antennas [2] are becoming relevant for research because of the constant expansion of the operating frequency band of communication systems. To calculate the aperture antenna field on a monochromatic (narrowband) signal, either the aperture or current method of field calculation is usually used [1–5].

The method of physical optics in the time domain, in which the integration contour is determined on the diffuser surface, is used in Refs. [6–18]. An analog of the physical optics method in the time domain is the aperture method [19–24].

In the aperture method, the Huygens element is often used as the aperture element. The normalized amplitude directional pattern of the Huygens element antenna is determined using the following equation:

$$\alpha\left(\vec{r},\vec{r}_a\right)=\left(1+\cos\left(\gamma\right)\right)/2,$$

where $\vec{r}$ is the radius vector from the aperture point $\vec{r}_a$ to the observation point and γ is the angle between the normal vector to the surface and the direction to the observation point. However, this directional pattern is valid only for free space field components. Other representations of the antenna directional pattern of an elementary radiator $\alpha\left(\vec{r},\vec{r}_a\right)$ are employed for different tasks. Sometimes this factor can be expressed as $\cos(\gamma)$ [4].

The theory of aperture antennas [1–6] assumes that the current on the metal surface $\vec{J}^e$ is equal to $\vec{J}_e=2\left[\vec{n},\vec{H}_S\right]$, where $\vec{n}$ is the normal vector to the aperture and $\vec{H}_S$ is the magnetic field on the aperture surface. This equation is true if the aperture surface is perfectly conductive and has infinite dimensions.

An aperture surface element S can be considered an elementary electric emitter (elementary dipole) if magnetic field lines act tangentially to it, but there are no tangential electric field lines. Thus, it can be considered an element of a long wire with infinite conductivity. The linear size l of the element must satisfy the condition $l=\lambda$. Under the boundary conditions, during the transition from "ideal conductor (wire)" to "free space," the tangential component of the vector $\vec{E}$ is equal to zero, and the tangential component of the vector $\vec{H}$ is determined using the value of the surface current density.

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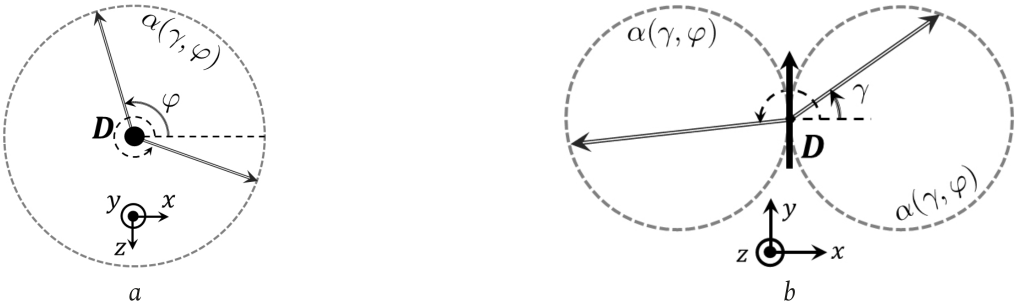


Fig. 1. Directional pattern of an electric dipole in the horizontal (*a*) and vertical (*b*) planes
Рис. 1. Диаграмма направленности электрического диполя в горизонтальной (*а*) и вертикальной (*б*) плоскостях

The spatially normalized amplitude directional pattern of an elementary electric dipole, presented in the form of a functional surface $F(\gamma,\varphi)$, is a three-dimensional figure. In practice, flat amplitude directional patterns depicting the dependence of the field strength values on the direction in one of the two main planes are usually used (Fig. 1).

1. Basic equations

The aperture theory based on physical optics assumes that the transfer function of an aperture with a uniform field distribution can be determined using the spatial frequency dependence of the emitter field on a certain polarization [1]:

$$E(\vec{r},\omega)=\frac{j\omega}{2\pi c}\iint_{S_a}\frac{g(\vec{r}_a)\alpha(\vec{r},\vec{r}_a)e^{j\omega|\vec{r}-\vec{r}_a|/c}}{|\vec{r}-\vec{r}_a|}dS_a, \qquad (1)$$

where ω is the circular frequency, c is the speed of light, S_a is the surface of the aperture, $g(\vec{r}_a)$ is the illumination function of the aperture, and $\alpha(\vec{r},\vec{r}_a)$ is the polarization factor, which is determined using the directional pattern of the elementary emitter of the aperture.

For ultra-wideband pulse signals, working with the time representation of the signal is more convenient. As reported in Ref. [6], each point of the aperture can be assumed to emit a δ-pulse at time $t=0$. The antiderivative of the impulse response (AIR) $\hat{E}(\vec{r},t)$ at point $\vec{r}$ can be obtained with the following form [6]:

$$\hat{E}(\vec{r},t)=\frac{1}{2\pi c}\iint_{S_a}\frac{g(\vec{r}_a)\alpha(\vec{r},\vec{r}_a)\delta\left(t-\frac{|\vec{r}-\vec{r}_a|}{c}\right)}{|\vec{r}-\vec{r}_a|}dS_a. \qquad (2)$$

Therefore, if the idealization we adopted is used, then this shape is a representation of the field, and the emitted signal is a δ-pulse. Given that the aperture field is proportional to the partial derivative of the input current with respect to time, in many cases, working with the derivative of the AIR is more convenient because it is simpler and more intuitive.

We assume that the energy of the pulse signal $S_{in}(t)$ is concentrated mainly in the frequency band $\omega_{min}\ll\omega\ll\omega_{max}$ and $\lambda_{max}\ll D$, where D is the circular aperture diameter, or $\lambda_{max}\ll 2R$, where R is the radius of the aperture. Although Eq. (2) would be formally incorrect, in this case, it will provide the correct result for the signal at the antenna input $S_{in}(t)$ (for more details, see Refs. [3] and [6]).

Thus, this is the most convenient way of calculating the representation of the field of the emitted δ-pulse, the derivative of the AIR, and the convolution of the impulse response and the input pulse according to Eq. (3).

As a result, using Eq. (2) and a given signal at the antenna input $S_{in}(t)$, we obtain the equation for the field at any point in front of the aperture, considering the assumption that the entire system is linear [6]:

$$S_{\vec{E}}(\vec{r},t)=S_{in}(t)\otimes\frac{\partial\hat{E}(\vec{r},t)}{\partial t}=S_{in}(t)\otimes h(\vec{r},t), \qquad (3)$$

where $\hat{E}(\vec{r},t)$ is the AIR, the function $h(\vec{r},t)$ is the aperture impulse response, and the symbol ⊗ denotes the convolution in time. As reported in Ref. [6], $\hat{E}(\vec{r},t)$ can be expressed as follows:

$$E(\vec{r},t)=\frac{1}{2\pi}\int_{\varphi_1}^{\varphi_2}g(\vec{r_a}\in C_a)\alpha(\vec{r},\vec{r}_a\in C_a)d\varphi, \qquad (4)$$

where $\vec{r}$ is the radius vector from a point on the aperture $\vec{r}_a$ to observation point A (Fig. 2*a*), the contour C_a is a circle with the radius $r_{ct}=\sqrt{(ct)^2-z^2}$ (Fig. 2*b*) and center at $\vec{r}_0$ (where $\vec{r}_0$ is the projection of the vector $\vec{r}$ onto the aperture plane), and t is the time. The integral is taken over the angle φ that describes the arc of the circle C_a with its center in $\vec{r}_0$. The limits of integration φ_1 and φ_2 depend on the position $\vec{r}$ in such a way that both values can vary from 0 to 2π. Let us assume that the distribution of the aperture amplitude is constant over the entire plane of the aperture $g(\vec{r}_a)=1$. Let us rewrite the polariza-

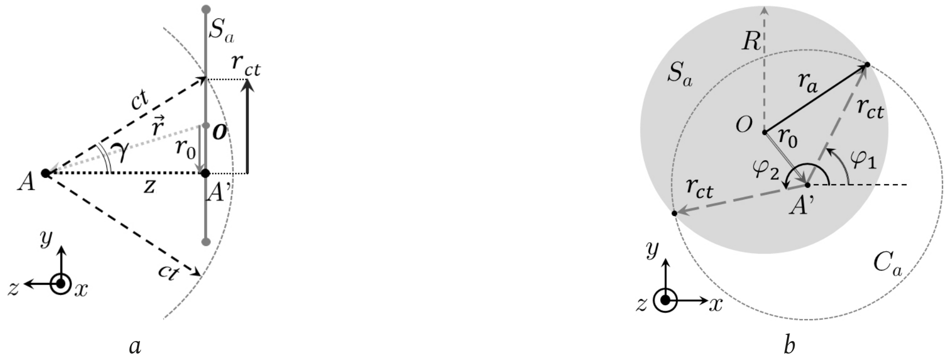


Fig. 2. Aperture S_a and imaginary sphere with radius *ct* (*a*); aperture S_a, integration contour C_a and angle φ (*b*)
Рис. 2. Апертура S_a и воображаемая сфера с радиусом *ct* (*а*); апертура S_a, контур интегрирования C_a и угол φ (*б*)

tion multiplier or the dependence of the directional pattern of the aperture elementary emitter $\alpha\left(\vec{r},\vec{r}_a\right)$ as a function of angles γ and φ as follows:

$$\alpha\left(\vec{r},\vec{r}_a\right)=\alpha\left(\gamma\left(\vec{r},\vec{r}_a\right),\varphi\left(\vec{r}_a\right)\right). \quad (5)$$

For the AIR, the integral is derived as follows:

$$\hat{E}\left(\vec{r},t\right)=\frac{1}{2\pi}\int_{\varphi_1}^{\varphi_2}\alpha\left(\gamma,\varphi\right)d\varphi. \quad (6)$$

A simple equation for γ can be obtained from Fig. 2 as follows:

$$\cos\left(\gamma\right)=z/ct. \quad (7)$$

As described previously, $\cos\left(\gamma\right)=\alpha\left(\gamma,0\right)$ is the directional pattern of a vertically located elementary dipole (or the directional pattern of an elementary emitter of a flat metal surface of infinite conductivity) in the vertical plane (Fig. 1). In the horizontal plane, the diagram of such an emitter is constant $\alpha\left(0,\varphi\right)=1$.

Therefore, in the time domain, an equation for the multiplier $\alpha\left(\gamma(t),\varphi(t)\right)$, which will describe the correct change in the value of $\hat{E}\left(\vec{r},t\right)$, must be obtained. The directional pattern of an elementary electric dipole in spatial form is a round torus with a center in the dipole middle and equal internal and external radii. Fig. 3 shows the dipole and its directional pattern in three dimensions. Let us assume that the field strength $\vec{E}$ is collinear to the *y*-axis.

When calculating the integral of Eq. (6), the polarization multiplier α cannot be extracted from the integral because, for each angle φ in the integration process, the value of the antenna directional pattern in the torus section along a certain direction (γ, φ) needs to be considered. This action is attributed to the radius vector $\vec{r}_{ct}$ and, accordingly, the cross-section of the directional pattern of each vertical dipole that rotates about the vertical axis *y* when passing through different values of angle φ. Therefore, at each point of the arc C_a, the polarization multiplier has a different value because it describes the length of the radius of the torus section toward the angle γ. Fig. 3 shows that the integration operation is performed in the first quarter of the *YOX* plane.

Fig. 4 shows the relative positions of the circular aperture S_a, the integration contour C_a, and various directional patterns $\alpha\left(\gamma,\varphi\right)$ depending on the integration angle φ.

The cross-section of a circular torus with a plane parallel to its axis of rotation is well-known and extensively investigated [8]. Such sections represent the curves of the Perseus or Cassini ovals. The canonical equation of a torus with the axis of symmetry *y* is expressed as follows:

$$\left(\sqrt{z^2+x^2}-Q\right)^2=y^2+q^2, \quad (8)$$

where *x*, *y*, and *z* are the Cartesian coordinates, *Q* is the distance from the axis of symmetry to form a circle (at the center of the figure of rotation), and *q* is the radius of the forming circle (figure of rotation). The canonical equation for the cutting plane is expressed as follows:

$$y=\tan\left(\varphi\right)x, z=\forall\in\mathbb{R}. \quad (9)$$

After some rearrangements and transformations, we obtain the following equation for the radius of the cross-section:

$$r_{cs}=\alpha\left(\gamma,\varphi\right)=\sqrt{1-\sin^2\gamma\sin^2\varphi}. \quad (10)$$

By substituting γ in Eq. (7), we rewrite the equation as follows:

$$\alpha\left(t,\varphi\right)=\sqrt{1-\left(1-\left(z/ct\right)^2\right)\sin^2\left(\varphi\right)}. \quad (11)$$

Eq. (11) is a new equation for the polarization factor of an elementary emitter of a metal flat surface with infinite conductivity in the time domain.

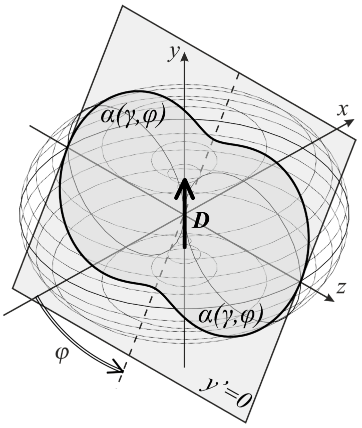


Fig. 3. Dipole *D* and its radiation pattern in three dimensions
Рис. 3. Диполь *D* и его диаграмма направленности в трех измерениях

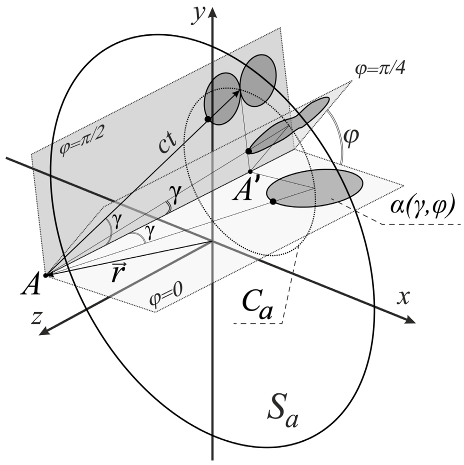


Fig. 4. Circular aperture S_a, contour C_a and different radiation patterns $\alpha(\gamma,\varphi)$ depending on the angle of integration φ
Рис. 4. Круглая апертура S_a, контур C_a и различные диаграммы направленности $\alpha(\gamma,\varphi)$ в зависимости от угла интегрирования φ

Notably, Eq. (11) refers to a metal flat aperture, regardless of its shape.

Eq. (6) for the AIR considering the polarization multiplier of Eq. (11) is rewritten as follows:

$$E(\vec{r},t)=\frac{1}{2\pi}\int_{\varphi_1}^{\varphi_2}\sqrt{1-\left(1-\left(\frac{z}{ct}\right)^2\right)\sin^2(\varphi)}d\varphi. \quad (12)$$

If we input the parameter $\beta=1/\left(1-(z/ct)^2\right)$, then the integral of Eq. (12) can be transformed into the following expression:

$$E(\vec{r},t)=\frac{1}{2\pi\beta}\int_{\varphi_1}^{\varphi_2}\sqrt{\beta-\sin^2(\varphi)}d\varphi\times \left(\frac{\sqrt{2\beta+\cos(2\varphi)-1}}{\sqrt{2\beta+\cos(2\varphi)-1/b}}\right)E\left(\varphi|\frac{1}{\beta}\right), \quad (13)$$

where $E(\varphi|1/\beta)$ is a second-order elliptic integral with the parameter $1/\beta$. This integral is a table integral and cannot be expressed in the form of elementary functions. Such integrals were first investigated by Giulio Fagnano and Leonhard Euler in the mid-18th century [25]. The second-order elliptic integral yields the arc length of an ellipse. Both first-order and second-order elliptic integrals are available for calculation in MATLAB. In general, Eq. (13) can be used for a flat aperture of any shape. At each instance of time *t*, the angles of integration φ_1 and φ_2 along a part of the circle C_a are determined by the points at which this contour intersects with the boundary of the aperture S_a. In some cases, a rectangular aperture may have several such segments on the line of integration [10], and the integral will consist of the sum of the integrals over these segments.

2. Calculation results

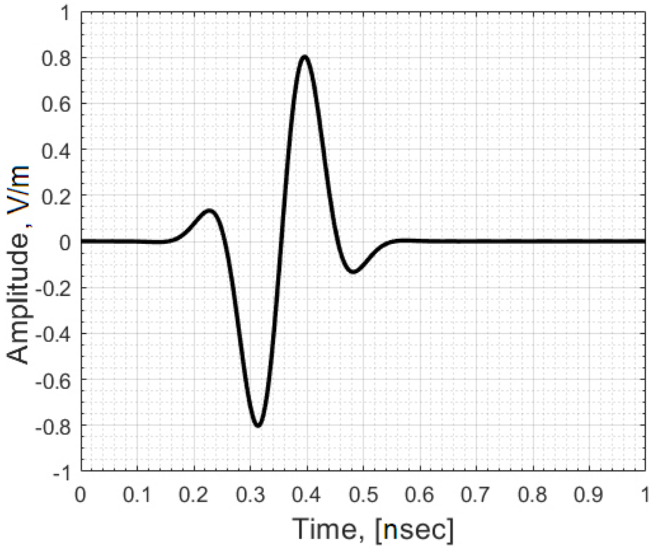
Let us compare the results of calculating the time dependence of the field obtained using the proposed calculation method for three different polarization multipliers and the results of numerical simulation using the finite integration technique (FIT).

Calculations using the model were performed within the countable volume. The distance from the aperture surface to the boundaries along the *X*- and *Y*-axes was 0,5 m. The reflectance coefficient of perfectly matched layers was 10^{-5}. The number of hexagonal grid cells into which the calculated volume was divided was 200 million in a quarter of the volume. Adaptive mesh formation was used, and smaller cells were created in the vicinity of structural inhomogeneities.

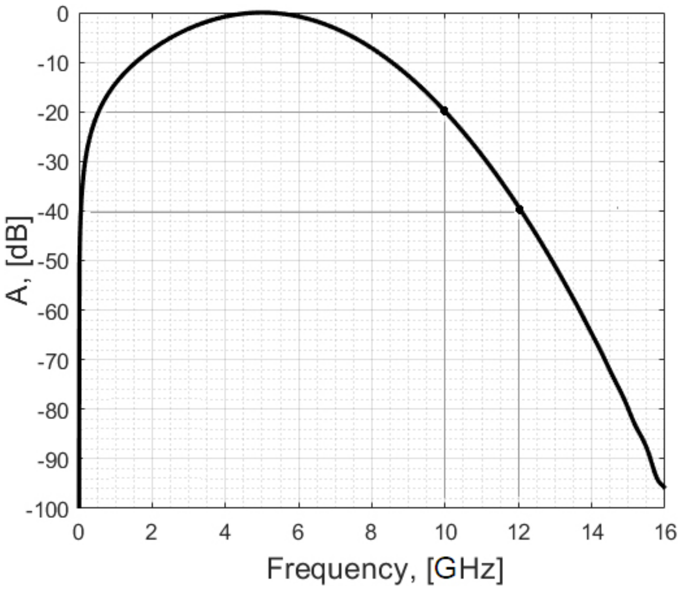
A linearly polarized plane wave propagated from the boundary of the countable volume perpendicular to the circular aperture. The zero moment of the analysis time was considered to be the moment of reflection from a flat round plate. Infinitely small linearly polarized field probes were placed in front of the quasi-aperture.

Because of the need to limit the frequency band in the FIT, a bipolar Gaussian ultra-wideband (UWB СШП) ultrashort pulse (Fig. 5*a*) with a spectrum from 1 MHz to 10 GHz at a level of –20 dB and up to 12 GHz at a level of –40 dB was used to excite a plane wave in the simulation (Fig. 5*b*).

The signal on the probe obtained numerically (dashed line) and the convolution of the input signal (Fig. 5*a*) with three theoretical impulse responses derived from Eq. (13) for various polarization multipliers are shown in Figs. 6 and 7.



a



b

Fig. 5. Bipolar Gaussian UWB signal (*a*); spectrum of this signal (*b*)
Рис. 5. Биполярный гауссовский UWB-сигнал (*a*); спектр этого сигнала (*б*)

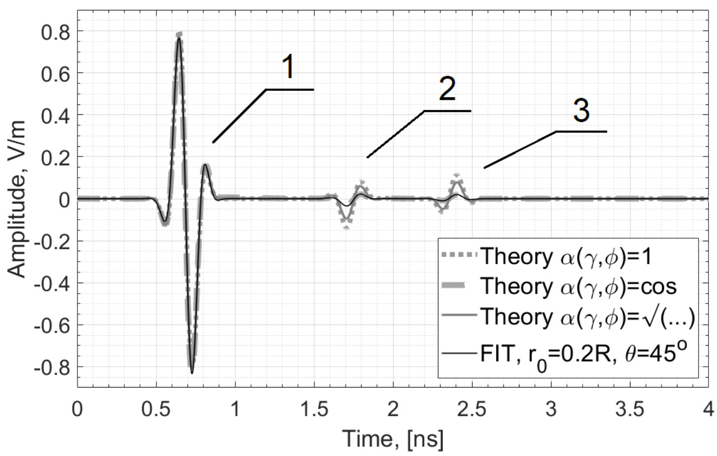


Fig. 6. Probe signals obtained numerically with FIT (thin black solid line) and convolution with theoretical IRFs for three different $\alpha(\gamma,\varphi)$
Рис. 6. Сигналы на зондах, полученные численно с помощью FIT (тонкая черная сплошная линия) и свертки с теоретическими IRF для трех различных $\alpha(\gamma,\varphi)$

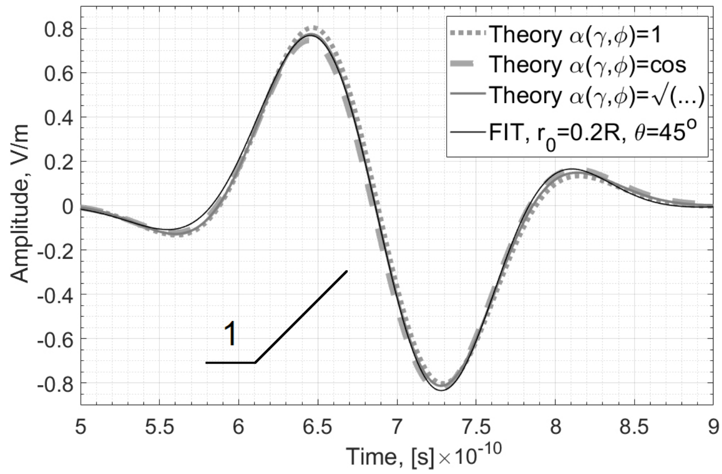


Fig. 7. Probe signals obtained numerically with FIT (thin black solid line) and convolution with theoretical IRFs for three different $\alpha(\gamma,\varphi)$
Рис. 7. Сигналы на зондах, полученные численно с помощью FIT (тонкая черная сплошная линия) и свертки с теоретическими IRF для трех различных $\alpha(\gamma,\varphi)$

The probe is located at the point $r_0 = 0,2R$, $z = 0,2R$, $\theta = \pi/4$. Here, r_0, z, and θ are the cylindrical coordinates, with r_0 being the distance from the z-axis and θ being the angle from the x-axis. Pulse 1 in Figs. 6 and 7 is the main pulse, and Pulses 2 and 3 in Fig. 6 are caused by boundary and edge effects [6].

Fig. 7 presents an enlarged view of the main pulse shown in Fig. 6. Notably, the main shape of the pulse is nearly the same for all polarization factors, which indicates the pulse of the main wave. However, its maximum amplitude and mid-zero crossing time (approximately 6,9 ns) are different. The difference in the maximum amplitude of the pulse obtained by the FIT and the pulse calculated using Eq. (11) is approximately 0,5 %; this difference is approximately 2,5 % for a "cosine" polarization multiplier and approximately 4 % for an isotropic emitter.

On the z-axis, when $r_0 = 0$, only two pulses can be recorded, namely, the main pulse and the sum of the boundary and edge effects that arrive simultaneously at this point from the circular aperture. In any other case inside the aperture or projecting ray, when $r_0 \neq 0$, the signal from the aperture will have three pulses. When considering a point outside the projecting ray, two boundary pulses with opposite signs are noted from the nearest boundary and the opposite edge.

A comparison of the signals calculated using the FIT and the method proposed in this study showed that the amplitudes of Pulses 2 and 3 corresponding to the rear part of the AIR are different. The largest difference is noted near the z-axis. These deviations are determined and explained by the antenna directional pattern of the elementary emitter and the effect associated with the flow of currents at the aperture boundary. The signal amplitude at the probe obtained by the FIT is smaller than that obtained by the theoretical calculations. Notably, the edge currents at the boundary compensate for/reduce the secondary impulses.

Conclusion

This study presents a new analytical equation in the time domain of Eq. (11) for the directional pattern of an elementary radiator of an antenna flat aperture depending on the time and angle of integration. A new equation (i.e., Eq. (13)) for the AIR of a circular aperture in the form of a second-order elliptic integral is also obtained. The last equation can be applied to a flat aperture of any shape. The shape of the flat aperture expressed in Eq. (13) was determined using only the integration segment or, in several cases, several segments.

The resulting equations for the field enable more accurate calculations of the field of large flat metal apertures, where numerical calculation methods (i.e., FIT and the method of moments) encounter difficulties in implementing the terms of time and computational costs. Thus, through the use of an analytical method based on physical optics and aperture theory in the time domain, the accuracy of the method for a linearly polarized field is improved.

The proposed method can be used to solve problems associated with the spatial distribution of the linearly polarized field of aperture antennas more easily and with higher accuracy.

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Линейно поляризованное поле плоской апертуры

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Аннотация – В статье проводится анализ плоской круглой апертуры и предлагается к использованию новое аналитическое выражение, описывающее диаграмму направленности элементарного излучателя апертуры антенны в зависимости от времени и угла интегрирования. Представленная в работе формула может применяться к любому плоскому участку апертуры без учета его формы. Приведено новое уравнение для первообразной функции импульсной характеристики круглой апертуры в виде эллиптического интеграла второго рода. Показано, что теоретически рассчитанные по формулам результаты хорошо согласуются с численным моделированием. При анализе численной модели использовался метод конечного интегрирования во временной области (FIT). Вследствие требования большого вычислительного ресурса численная модель представлялась упрощенной.

Ключевые слова – апертура; ЭМ-волна; линейная поляризация; импульсная характеристика.

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