USE OF MULTILAYER DIELECTRIC FOR SLOT PHASED ARRAY ANTENNAS

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ABSTRACT

It is of interest to study slot spiral radiators as part of a phased array with structural elements in the form of multi-layer dielectrics that make up a multilayer substrate and a spiral cover, which, by changing the parameters of a multilayer dielectric, can significantly change the frequency properties of the radiator and its overall dimensions. The purpose of the work is to develop a mathematical model for a phased array in the form of a periodic structure with slotted spiral radiators using multilayer dielectrics in the design, and its numerical analysis with the study of its frequency properties when choosing the topology of the spiral, the parameters of the dielectric layered medium, followed by determining the design dimensions of the spiral as an element of the phased antenna arrays. A mathematical model of a phased array is presented in the form of a periodic structure with slotted radiators using multi-layer dielectrics in the design. The method is based on the conversion of the electrodynamic problem of excitation to an integral equation with its subsequent transformation to a one-dimensional Fredholm integral equation of the first kind. The directional and polarization characteristics of the phased antenna arrays element are determined, and a numerical analysis of its frequency properties is carried out.

KEYWORDS: *Phased array antenna, slot antenna, multilayer media, integral equations, self-regularization method.*

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1 Introduction

A flat spiral radiator made on the basis of a microstrip or slot structure can be considered as one of the promising radiating elements of rotating polarization of phased antenna arrays (PAA) [1, 2]. To build broadband phased array, the emitter has sufficiently good frequency properties [3,4], almost the same width of the radiation pattern in orthogonal planes that determine the scanning angle of the array, is characterized by a low protruding design and small transverse dimensions, convenient for placement in the array.

It is of interest to study slot spiral radiators as part of a phased array with structural elements in the form of multilayer dielectrics that make up a multilayer substrate and a spiral cover, which, by changing the parameters of a multilayer dielectric, can significantly change the frequency properties of the radiator and its overall dimensions.

The purpose of the work is to develop a mathematical model for a phased array in the form of a periodic structure with slotted spiral radiators using multilayer dielectrics in the design, and its numerical analysis with the study of its frequency properties when choosing the topology of the spiral, the parameters of the dielectric layered medium [5], followed by determining the design dimensions of the spiral as an element of the phased antenna arrays.

Mathematical modeling is based on the conversion of the electrodynamic problem of excitation of a slotted helix with a multilayer dielectric in a spatial cell of a periodic lattice to an integral equation for the magnetic current of the helix, followed by its transformation to a one-dimensional Fredholm integral equation of the first kind. For the numerical solution of the latter, an efficient algorithm based on the principle of self-regularization is used [5]. For a known current of a spiral array element, its directional and polarization characteristics are determined, and a numerical analysis of the frequency properties of the PAA elements is carried out depending on the choice of the spiral topology, the spatial cell of the periodic array, and the parameters of the layered dielectric filling. In addition, the layered media may include a loaded shield characterized by a surface impedance.

2 Method for solving an electrodynamic problem

An unlimited periodic lattice of flat slotted spirals is considered (Fig. 1).

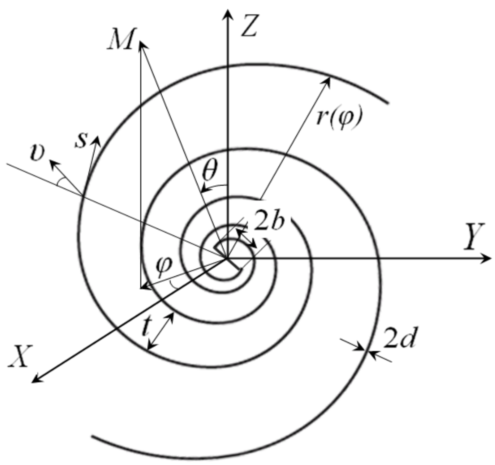

Fig. 1. Geometry of the slotted helix

On one of the boundaries of the layered medium, representing the transverse filling of the cell, there is a slit structure S_s in the form of a two-start spiral, the geometry of which is characterized by a generatrix in the form of a smooth curve (Fig. 1).

The spiral arms have length 2*L* and width 2*d*, $kd \ll 1$, $kL > 1$, where $k = 2\pi / \lambda$, λ is the working wavelength. The geometry of the generatrix is described by an orthogonal coordinate system (s, ν) with elements of length $dl = h_1 ds$, $dt = h_2 d\nu$, where h_1, h_2 are the Lame coefficients. The spiral entry is represented by a narrow slit of width $2d$ and length $2b$, $kd \ll 1$, $kb \ll 1$, aligned with the nodes of a rectangular lattice grid with periods D_x, D_y.

The medium (Fig. 2) models the properties of a layered substrate and a spiral cover and is characterized by parameters $\varepsilon(z)$, μ_0 and may contain a screen with surface impedance as a boundary layer Z_s.

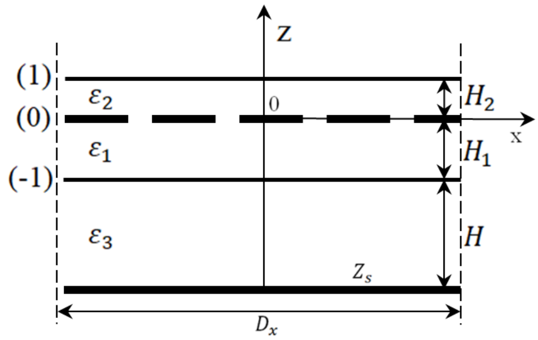

Fig. 2. Multilayer backing and spiral cover into grid cells

We will assume that for a given potential difference at the inputs of spiral radiators, the latter in the array are excited with the same amplitude and linear phase shift. The phase of the emitter with a number (*m, n*) is defined as $\psi_{mn} = m\psi_x + n\psi_y$, where ψ_x, ψ_y are the guiding phases, which are related to the direction of the wave vector $\mathbf{k}$ characterizing the direction (θ, φ) of the main radiation of the grating (Fig. 1): $\psi_x = kD_x \sin\theta \cos\varphi$, $\psi_y = kD_y \sin\theta \sin\varphi$.

Under the indicated excitation, the grating field satisfies the conditions of almost periodicity (Floquet conditions), so that it suffices to consider it within the spatial cell of the grating (Floquet channel).

The inversion of the electrodynamic problem of excitation of a periodic lattice and the derivation of an integral equation for the magnetic current of a spiral radiator in the Floquet channel are carried out in detail in [6, 7, 8]. The field $\mathbf{E}$, $\mathbf{H}$ of a slotted helical lattice element in the Floquet channel with current $\mathbf{j}_s^M(M_0)$ is expressed using the vector potential $\mathbf{A}^M$,

$$\mathbf{A}^M = \frac{\mu_0}{4\pi} \iint\limits_{S_{щ}} \mathbf{j}_s^M(M_0) \hat{G}^M(M, M_0) \, d\sigma_{M_0}, \tag{1}$$

where M, M_0 are the observation and source points, $\hat{G}^M$ and is the Green's tensor of the layered medium for the magnetic source. For representation (1), the field vectors $\mathbf{E}$, $\mathbf{H}$ are determined from the relations

$$\mathbf{H} = -i\omega\mathbf{A}^M - \frac{i}{\omega\mu_0}\operatorname{grad}\left(1/\varepsilon(z)\operatorname{div}\left(\mathbf{A}^M\right)\right)$$
$$\mathbf{E} = -\frac{1}{\varepsilon(z)} rot\,\mathbf{A}^M$$

In matrix form, the Green's tensor has the form [5],

$$\hat{G}^M = \begin{vmatrix} G_0^M & 0 & 0 \\ 0 & G_0^M & 0 \\ \varepsilon(z)\dfrac{\partial g^M}{\partial x} & \varepsilon(z)\dfrac{\partial g^M}{\partial y} & \dfrac{\varepsilon(z)}{\mu_0}G_1^M \end{vmatrix}, \tag{2}$$

where G_0^M, g^M, G_1^M are elements of the tensor Green's function. The elements of the tensor depend on the coordinates of the points $M_\perp$, $M_\perp^0$ the cross section $S_\perp$ of the Floquet channel, and the points z, z_0. An arbitrary element of the tensor G_α can be represented by a series expansion in a complete system of functions in the section $S_\perp$ satisfying the Floquet condition with parameters ψ_x, ψ_y [9]. Then the decomposition looks like:

$$G_\alpha(M, M_0) = \sum_{m=-\infty}^{\infty}\sum_{n=-\infty}^{\infty}\frac{1}{D_x D_y i\gamma_{mn}} U_{mn}(x,y) U_{mn}^*(x_0,y_0) G_{mn}^*(\lambda_{mn}, z, z_0), \tag{3}$$

where $U_{mn}(x,y) = \exp\left(i\left(\lambda_m x + \lambda_n y\right)\right)$, $\gamma_{mn} = \sqrt{k^2 - \lambda_m^2 - \lambda_n^2}$, $\lambda_m = k_x + 2\pi m / D_x$, $\lambda_n = k_y + 2\pi n / D_y$, $k_x = \psi_x / D_x$, $k_y = \psi_y / D_y$, $k = \omega\sqrt{\varepsilon(z)\mu_0}$, $\lambda_{mn} = \lambda_m^2 + \lambda_n^2$, $m, n = 0, \pm 1, \pm 2 \ldots$.

The system of functions $\{U_i\}_{i=0}^{\infty}$, where *i* is the index uniting the indices (*m, n*), is a complete orthonormal system that satisfies $S_\perp$ the Floquet conditions on the section contour. The function $G_{mn}^*(\lambda_{mn}, z, z_0)$ in (3) is defined as a discrete analogue of the corresponding element of the tensor from [9] for the parameter λ_{mn}.

The inversion of the electrodynamic problem and the derivation of the integral equation for the current $\mathbf{j}_s^M$ of a slotted helix in a spatial cell are carried out similarly to the technique from [7, 9]. The integral equation has the form

$$\iint_{S_{щ}} \mathbf{j}_s^M(M_0) K(M, M_0)\, d\sigma_{M_0} = -iU\sin\left(k|l|\right) + C_1\sin kl + C_2\cos kl \tag{4}$$

where $M \in \Gamma$, $M_0 \in S_щ$, U are the potential difference at the input of the slotted helix, the coefficients C_1 and C_2 are determined from the additional condition of the absence of magnetic current "draining" from the ends of the helix branches. The kernel $K(M, M_0)$ of the integral equation (4) contains elements of the Green's tensor (2) and has the form

$$K(M,M_0)=(\mathbf{s}^0,\mathbf{s}_0^0)\left[G_0^м(M,M_0)+\frac{\partial g^м(M,M_0,z)}{\partial z}\right]-\frac{1}{2}\int_\Gamma(\mathbf{s}_u,\mathbf{s}_0^0)\frac{\partial g^м(M_u,M_0,z)}{\partial z}\sin|l-u|\,du \quad (5)$$

The elements $G_0^м(M, M_0)$ and $\frac{\partial g^м(M, M_0, z)}{\partial z}$, included in the kernel (5), at $M \to M_0$ have a singularity, the order of which is $O(1/\rho_{MM_0})$. This feature defines Eq. (4) as an integral Fredholm equation of the first kind for the current $\mathbf{j}^м(M_0)$. Identification of this singularity in representations (3) improves the convergence of these expansions outside the singularity point and leads to the construction of an algorithm for a stable numerical solution of the integral equation.

For a narrow slot structure, S_s the $kd \ll 1$ inflow current $\mathbf{j}_s^м(M_0)$ can be represented by the longitudinal component $\mathbf{j}_s^м = \mathbf{s}^0 j_s^м$ and use the representation [9]

$$j_s^м(l,t)=I^м(l)/\sqrt{d^2-t^2} \quad (6)$$

where $I^м(l)$ is the total magnetic current of the slot S_s.

Using representation (6), we can pass to the one-dimensional integral equation for the total current $I^м(l)$ of the gap structure

$$\int_\Gamma I^м(l_0)\hat{K}(l,l_0)\,dk_0=-i\frac{U}{kd}\sin(k|l|)+C_1\sin kl+C_2\cos kl$$

Denoting the size $\Delta = \max(2d, h)$, where h is a sufficiently small size, which is defined below as the discretization step in the numerical solution of the integral equation (6). The kernel of the equation in the domain $\rho(M, M_0) < \Delta$, taking into account the selected singularity in the indicated elements of the tensor, has the form

$$\hat{K}(l,l_0)=\frac{4}{\pi}A\frac{F\left(\frac{\pi}{2},\alpha\right)}{\sqrt{\rho_0^2+d^2}}+\frac{1}{D_xD_y}\sum_{m=-\infty}^{\infty}\sum_{n=-\infty}^{\infty}\left\{\mathrm{e}^{i(\lambda_m x+\lambda_n y)}\left(\mathbf{s}^0,\mathbf{s}_0^0\right)*\right.$$

$$\left.*\left[\left(G_{0l}^{M}+\frac{\partial g_l^{M}}{\partial z}-\frac{A}{\lambda l}\right)\mathrm{e}^{-i(\lambda_m x_0+\lambda_n y_0)}+\frac{4A}{\lambda_l}\hat{g}_l^{M}\right]--\frac{1}{2}\frac{\partial g_l^{M}}{\partial z}\int_{\Gamma}\left(\mathbf{s}_u,\mathbf{s}_0^0\right)S_m(l,u)\,du\right\} \quad (7)$$

where $\alpha=d/\sqrt{\rho_0^2+d^2}$, $F\left(\frac{\pi}{2},\alpha\right)$ is a complete elliptic integral of the 1st kind, $\rho_0(M,M_0)$, M, $M_0\in\Gamma$, $S_m(l,u)=\sin k\left|l-u\right|\mathrm{e}^{i(\lambda_m x(u)+\lambda_n y(u))}$, $\hat{g}_l^{M}$ is a special function, A and is a coefficient related to the singularity of the field of a point source in a layered medium.

For the region $\rho_0(M,M_0)>0$ where the kernel is regular

$$\hat{K}(l,l_0)=\frac{1}{D_xD_y}\sum_{l(m,n)}\mathrm{e}^{i(\lambda_m x(u)+\lambda_n y(u))}$$

$$\left\{\left(\mathbf{s}^0,\mathbf{s}_0^0\right)\left[G_{0l}^{M}+\frac{\partial g_l^{M}}{\partial z}\right]-\frac{1}{2}\frac{\partial g_l^{M}}{\partial z}\int_{\Gamma}\left(\mathbf{s}_u,\mathbf{s}_0^0\right)S_m(l,u)\,du\right\} \quad (8)$$

In turn, the elements of the tensor in (7) and (8) are defined as

$$G_{0l}^{M}(\lambda_l,z,z_0)=\left[\left(1-R_0^E\right)\mathrm{e}^{-\eta_2(z-z_0)}-\right.$$

$$\left.-R_1^E\mathrm{e}^{-2\eta_2H_2}\left(1-R_0^E\right)\mathrm{e}^{\eta_2(z-z_0)}\right]\frac{1}{1-R_0^ER_1^E\mathrm{e}^{-2\eta_2H_2}}\frac{\lambda_l}{\eta_2}, \quad (9)$$

$$\frac{\partial g_l^{M}}{\partial z}(\lambda_l,z,z_0)=$$

$$\left\{\frac{R_0^E\mathrm{e}^{-\eta_2(z-z_0)}+R_1^E\mathrm{e}^{-\eta_2H_2}\left(1-R_0^E\right)\mathrm{e}^{\eta_2(z-z_0)}}{1-R_0^ER_1^E\mathrm{e}^{-2\eta_2H_2}}+\right.$$

$$\left.+\frac{R_0^H\mathrm{e}^{-\eta_2(z-z_0)}+R_1^H\mathrm{e}^{-2\eta_2H_2}\left(1+R_0^H\right)\mathrm{e}^{\eta_2(z-z_0)}}{1-R_0^HR_1^H\mathrm{e}^{-2\eta_2H_2}}\right\}\frac{\eta_2}{2\lambda_l}$$

$$\eta_0=\sqrt{\lambda_l^2-\varepsilon_0},\ \eta_1=\sqrt{\lambda_l^2-\varepsilon_1},\ \eta_2=\sqrt{\lambda_l^2-\varepsilon_2}.$$

The reflection coefficients from the layer boundaries (0) and (1) $R_0^{E,H}$ are $R_1^{E,H}$ determined according to the method [9].

For the numerical solution of equation (6) with a kernel in representations (7), (8), the self-regularization method [9] is most suitable, which, when the equation is discretized in a selected set of collocation points, leads to a stable numerical solution of the system of linear algebraic equations (SLAE) due to the predominance of the diagonal elements of the SLAE matrix, which is due to the feature of the kernel (7).

By calculating the current of the spiral emitter from the solution of the SLAE for each scanning angle, it is possible to determine the characteristics of the phased array. For the components E_θ, E_φ the radiation field of a spatial cell with a $I^M(l)$ slotted helix current, one can obtain the expressions

$$E_{\theta,\varphi} = ik\frac{W}{4\pi}\int_\Gamma I^M(l_0)F_{\theta,\varphi}\mathrm{e}^{ik(h_1 l_0 + r_0)(\mathbf{s}^0,\mathbf{s}_0^0)\sin\theta}dl_0,$$

where $F_\theta = \cos\theta\left[h_1(\mathbf{s}^0,\mathbf{s}_0^0) - h_2(\mathbf{v}^0,\mathbf{s}_0^0)\right]f_G(\theta)\cos\theta + i(\mathbf{s}^0,\mathbf{s}_0^0)f_g(\theta)\sin\theta$, $F_\varphi = \left[h_1(\mathbf{v}^0,\mathbf{s}_0^0) - h_2(\mathbf{s}^0,\mathbf{s}_0^0)\right]f_G(\theta)\cos\theta$, $f_G(\theta)$, $f_g(\theta)$ are functions that take into account the properties of the layered filling of a spatial cell. For the domain $z > H_2$, $z_0 = 0$ for these functions we have,

$$f_G(\lambda) = (1 + R_1^E)\frac{1 - R_0^E}{1 - R_1^E R_0^E \mathrm{e}^{-2\eta_2 H_2}}\frac{\lambda}{\eta_0}$$

$$f_g(\lambda) = \frac{\varepsilon_0}{\varepsilon_2}\frac{1}{2\lambda}\left[\frac{R_0^E(1 + R_0^E)}{1 - R_1^E R_0^E \mathrm{e}^{-2\eta_2 H_2}} + \frac{R_0^H(1 + R_1^H)}{1 - R_1^H R_0^H \mathrm{e}^{-2\eta_2 H_2}}\right]$$

where, in addition to notation (9), we have $\lambda = \sin\theta$, $\eta_0 = -i\cos\theta$, $\eta_1 = -i\sqrt{\varepsilon_1 - \sin^2\theta}$, $\eta_2 = -i\sqrt{\varepsilon_2 - \sin^2\theta}$.

Of interest is the partial radiation pattern of the slotted helix, which is determined by the radiation field of the spatial cell of the grating in the “free excitation” mode, i.e. when a spiral emitter is excited by an incident wave in a feeder line with a wave impedance W_f while maintaining the amplitude and phase relationships for the PAA emitters. Then, for a given input impedance, Z_{en} the partial diagram is defined as

$$E_{\theta,\varphi}^0 = E_{\theta,\varphi}\frac{2Z_{en}}{Z_{en} + W_f}$$

For the known components, $E_{\theta,\varphi}$ the characteristics of the rotating polarization field are determined, in particular, the ellipticity coefficient K_e.

The range properties of the array depend on the range properties of the array emitters and are related to the dimensions of the array cell, its layered filling, and to the allowable scanning angles.

The known relation $D \le \lambda_{max} / (1+\sin\theta_{max})$, where D is the grating period, λ_{max} is the wavelength for the lowest frequency f_{min} of the operating range, θ_{max} is the maximum scanning angle. Typically, a cell period size is used that is equal to the maximum size of the radiating element of the array. For a spiral radiator, this size corresponds to the diameter $D = \lambda_{max} / \pi$.

Depending on the layered filling of the cell, which makes up the substrate and the shelter of the emitters, diffraction dips appear in the partial diagram, associated with the excitation of the spectrum of surface waves that limit the scanning sector of the grating. Therefore, the question arises of choosing the size of dielectrics and the thickness of the layered medium, which prevent the excitation of surface waves of one type or another [6].

A a two -start slotted helix was chosen as a grating emitter, the topology of which is described by the relations (Fig. 1) $r_1(\varphi) = b\mathrm{e}^{a\varphi}$, $r_2(\varphi) = b\mathrm{e}^{a(\varphi+\pi)}$, $\mathrm{tg}\psi = 1/a$. *N* – number of spiral turns, *a* – parameter characterizing the spiral curvature, *b* – spiral entry size. For the cell period size we have $D \ge D_{cn}$.

For the study, the dimensions of the helix $b = 0.1$, slot width $b = 0.08$, with four turns of the helix and the size of the grating period $D_x = D_y = 2.1$, where the linear dimensions are normalized so that $D = kD^0$ where $k = 2\pi / \lambda$, D^0 is the linear dimension, are chosen.

Changes in the characteristics of the slotted helix in the PAA, such as the input impedance Z_{en} and the coefficient of ellipticity, K_e are considered in the frequency range from $f_{min} = f_0$ to $f_{max} = 5f_0$. The spiral is located in a multilayer medium (Fig. 2) with parameters ε_1, ε_2 and ε_3 dimensions H_1, H_2 and H above the screen with surface impedance Z_s. In Figures 3 and 4 shows the indicated characteristics of the slotted helix in the phased array for the values $\varepsilon_1 = 6$, $\varepsilon_2 = 12$ and $\varepsilon_3 = 2.3$ at the thickness $H_1 = 0.25$, $H_2 = 0.25$ and $H = 0.1$ with the loaded screen $Z_s = -i60$ Ohm. Dependences of the input impedance are built on the normalized frequency *f* / *f* $_0$, the ellipticity factor - on the scanning angle θ. A loaded screen assumes the implementation of the impedance value Z_s by an additional structure in the sense of a "third-party impedance boundary condition". Figure 5 shows a partial radiation pattern calculated at three frequencies.

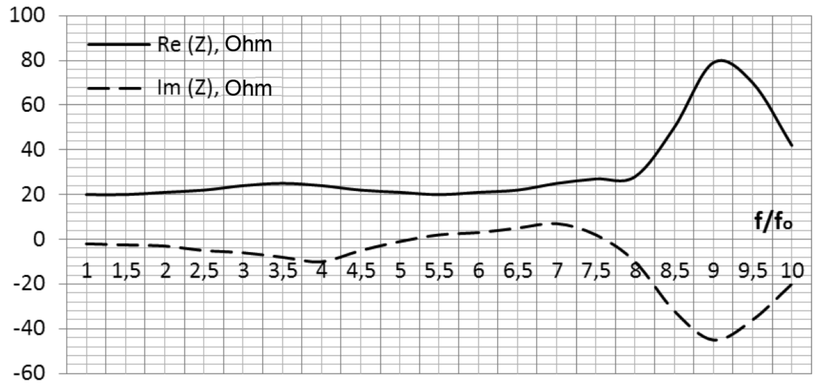

Fig. 3. Input impedance of the slotted spiral as part of the PAA

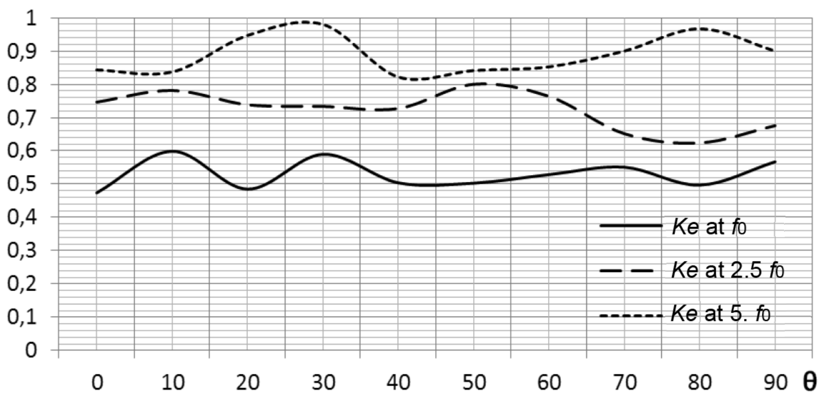

Fig. 4. Coefficient of ellipticity of the slotted helix as part of the PAA

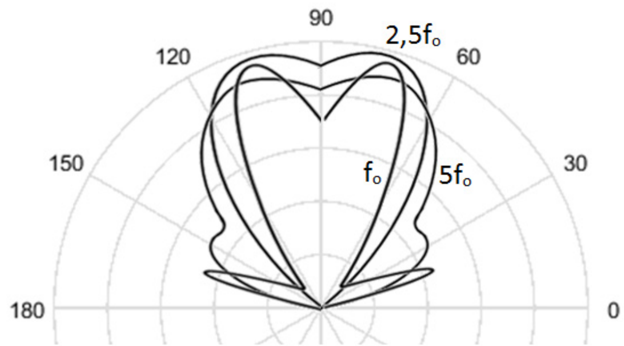

Fig. 5. Partial radiation pattern

3 Conclusion

Thus, a special selection of the parameters of multilayer media that form a layered substrate and shelter of slotted spirals in the PAA, as well as the use of loaded screens with surface impedance, can improve the frequency properties of the spirals and reduce the height of the screen suspension due to the creation of conditions that prevent the excitation of surface waves, which occur in a multilayer environment.

In this case, the condition of using a material with a higher dielectric constant as the upper layer of a multilayer medium and the choice of capacitive surface impedance are of fundamental importance.

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