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THE PRINCIPAL FACTORS DETERMINING THE DIRECTIONAL PATTERN OF A DIELECTRIC ANTENNA

by

G. Zh. Rankis

Izvestiya VUZOV SSSR - Radiotekhnika (Radio Engineering), Vol. IX, No. 1, 1966, pp. 97-104

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The directional pattern of a dielectric antenna is analyzed on the basis of integral equations. Additional factors are established which determine the difference of the directivity pattern of a real antenna from an idealized linear travelling-wave antenna: direct radiation of the exciting junction, a supplementary field in the region of the exciting junction, etc. Estimates of the magnitude of their influence were obtained for different varieties of dielectric antennas. The properties of conical dielectric antennas are briefly examined.

The basic idea of the theory and method of engineering calculation of dielectric antennas at the present time is the concept of the characteristic wave of an infinite dielectric waveguide as the main factor determining its directional pattern. Such a concept, in spite of extreme idealization of the actual conditions, at least explains the main features of the radiation pattern. Because of the physical simplicity and clarity of that model it is of interest to construct on the basis of it a more precise theory of a dielectric antenna. The purpose of the present work is to explain the main factors whose effect leads to deviation of the directional pattern of a real antenna from the idealized model. From that point of view the model can be considered a first approximation which will be refined later with consideration of other factors. The advisability of such an examination is confirmed still more by the fact that rigorous problems of the diffractional excitation of dielectric waveguides in the three-dimensional case have not been solved.

An Expression for the Directional Pattern

Let us examine a dielectric antenna protruding from an infinite plane ideally conducting screen (Figure 1). By applying the method of functions of elementary sources a system of integral equations can be derived for the field intensity.[1]

$$[\vec{E}(r), \vec{a}] - j\omega \int_V [\epsilon(r') - \epsilon_0] [\vec{E}(r'), \vec{E}_1(r, r')] \, dV'$$

$$= - \int_{S_0} \{[\vec{E}(r'), \vec{H}_1(r, r')], \vec{dS'}\} \quad , \qquad (1)$$

where $\vec{E}(r)$ is the field at the point of observation M, the set of coordinates of which we will designate by r, $\vec{E}_1(r, r')$; $\vec{H}_1(r, r')$ is the field of an elementary vibrator located at the point M in the direction $\vec{a}$ at the current point of the antenna r'; $\epsilon(r')$ is the distribution function of the dielectric constant over the volume of the antenna; $\vec{E}_\tau(r')$ is the field in the exciting aperture ($z = 0$).

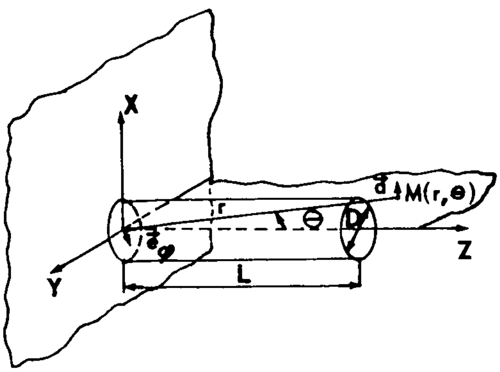

Figure 1

The single vector $\vec{a}$ can be expanded in three mutually perpendicular directions; therefore Eq. (1) decomposes into three scalar equations.

If the field within the dielectric and at S_0 is known, then a formula for calculation of the field created by the dielectric antenna follows from Eq. (1). For an antenna uniform in length and occupying the volume V_0 it assumes the form

$$[\vec{E}(r),\vec{a}] = j\omega(\epsilon - \epsilon_0)\int_{V_0} [\vec{E}(r'),\vec{E}_1(r,r')]\,dV' - \int_{S_0}\{[\vec{E}_\tau(r'),\vec{H}_1(r,r')],d\vec{S}\}. \quad (2)$$

We will use that formula to investigate the directional pattern. Let the plane XZ be E, the plane of the antenna. Let us examine the directivity pattern of the field of major polarization in the plane H(YZ). Then $\vec{a}$ must be directed parallel to the X-axis.

We will represent the field within the antenna in the form

$$\vec{E}(r') = \vec{E}_0(r') + \vec{E}'(r'), \quad (3)$$

where $\vec{E}_0(r')$ is the field of the characteristic wave of the dielectric waveguide, and $\vec{E}'(r') = \vec{E}_0(r') - \vec{E}_0(r')$ is the difference between the real field in the antenna and the field of the characteristic wave. We will call that difference the supplementary field. The field of the characteristic wave can be represented in the form

$$\vec{E}_0(r') = \vec{E}_0(x,y)\, e^{-jk_d z} e^{j\psi}.$$

With consideration of (3) and (4), expression (2) gives

$$E_a(x,y,z) = j\omega(\epsilon - \epsilon_0)\, e^{j\psi}\int_0^L e^{-jk_d z'}\,dz' \int_{S_T} [\vec{E}_0(x';y'),\vec{E}_1(x,y,z;x',y',z')]\,dx'dy'$$

$$+ j\omega(\epsilon - \epsilon_0) \int_{V_0} [\vec{E}'(x',y'), \vec{E}_1(x,y,z;x',y',z')]\, dx'dy'dz'$$

$$- \int_{S_0} \{ [\vec{E}_\tau (x',y',). \vec{H}_1 (x,y,z;x',y',z')], \vec{dS}' \}. \qquad (4)$$

Here the field intensity at the point of observation is represented as the sum of three components: the field created by the characteristic wave of the antenna, the field created by the supplementary field in the dielectric, and the field created by the exciting aperture. The first of them represents an approximation usually used at the present time.[2,3,4] Because it explains the character of the directional pattern in its principal features, certain simplifications can be introduced into the remaining terms, with confidence that the directional pattern will be changed little on account of that. Let us assume that the distribution function over the cross section of the antenna of all three fields entering Eq. (4) will be identical and agree with the distribution of the field of the characteristic wave:

$$\vec{E}_\tau (x',y') = \frac{1}{a} \vec{E}_0 (x',y'), \qquad (5)$$

$$\vec{E}' (x',y') = \vec{E}_\tau f'(z'). \qquad (6)$$

If we substitute in (4) Eq. (5) and (6) and also the expressions for $\vec{E}_1$ and $\vec{H}_1$, which in the distant zone have the form

$$\vec{E}_1 = -\vec{e}_x j \frac{60\pi}{\lambda r} e^{-jkr}, \qquad (7)$$

$$\vec{H}_1 = \vec{e}_\varphi j \frac{1}{\lambda r} e^{-jkr}, \qquad (8)$$

and also

$$r(x,y,z) = r(x,y) - z\cos\Theta,$$

after several transformations we obtain for the directional pattern the expression

$$F(\Theta) = F_0(\Theta)[F_1(\Theta) + F_2(\Theta) + F_3(\Theta)], \qquad (9)$$

where

$$F_1(\Theta) = \pi N(\epsilon' - 1)\, a e^{j\psi}\, \frac{\sin\alpha}{\alpha}\, e^{-j\alpha}, \tag{10}$$

$$F_2(\Theta) = -j\,\frac{\cos\Theta}{2}, \tag{11}$$

$$F_3(\Theta) = \pi N(\epsilon' - 1)\,\frac{1}{L}\int_0^L f'(z')\, e^{jkz'\cos\Theta}\, dz', \tag{12}$$

$$F_0(\Theta) = \int_{S_T} E_0(x',y')\, e^{-jkr(x',y')}\, dx'dy', \tag{13}$$

$$\alpha = \pi N(\xi - \cos\Theta), \tag{14}$$

$$N = \frac{L}{\lambda}, \tag{15}$$

$$\xi = \frac{k_a}{k} = \frac{c}{\upsilon_f} \tag{16}$$

υ_f is the phase velocity of the characteristic wave of the dielectric waveguide.

In order not to encumber the calculations too much we disregarded the influence of the ideally conducting screen here. Its role will be explained below.

In expression (9) the function $F_0(\Theta)$ is a multiplier of the element which was investigated by Fradin[2] for a cylindrical rod, and for a thin-walled dielectribe tube with the diameter D has the form

$$F_0(\Theta) = \cos\left(\frac{kD}{2}\sin\Theta\right). \tag{17}$$

In both cases it represents a function of the angle Θ which gradually varies within the limits of the major lobe and the first minor lobes.

In the multiplier of the element in brackets in (9) the second and third terms represent supplementary terms for expressing the directional pattern of a first approximation of the type $\sin\alpha/\alpha$.

Let us deal with investigation of their influence in more detail.

The Influence of Direct Radiation of the Exciting Junction

If only that supplementary factor is considered, for the directional pattern with respect to power we obtain the following expression after several transformations[5]

$$\Psi^2(\Theta) = F_1'^2(\Theta) + \frac{1}{\pi N(\epsilon' - 1) a} F_1'(\Theta) \cos\Theta \cos\left(\psi - a + \frac{\pi}{2}\right), \qquad (18)$$

where

$$F_1'(\Theta) = \frac{\sin\alpha}{\alpha} . \qquad (19)$$

It follows from Eq. (18) that at sufficiently small values of a the influence of the second term can be perceptible, especially in the region of the first minor lobes of the pattern. In that case, depending on the angle ψ, either increase or decrease of the level of the minor lobes is possible. If we establish a definite value of the angle ψ (by including at the beginning of the antenna a small section with a different phase velocity), we can substantially lower the level of the minor lobes of tubular antennas.[5,6]

Let us examine the coefficient a in more detail. We will express it by two values characterizing the exciting junction and the dielectric waveguide: ρ_1 is the power transmission coefficient of the exciting junction of the antenna (the effectiveness of the excitation), a method of experimental determination of which was given previously,[6] and

$$\rho_2 = \frac{W_i}{W_a} ,$$

where W_i and W_a are the fractions of power spreading in and outside the dielectric respectively. The latter value is found for a round rod in Fradin.[2] If the distribution of the field over the cross section is considered to be uniform and it also is assumed that the wave resistance of the dielectric waveguide is equal to the wave resistance of a vacuum (cf. Fradin,[2] p. 529) and equal to the amplitude ratio of the tangential components of the electric and magnetic fields on the exciting aperture, and then it can be found elementary arguments that

$$a = \sqrt{\frac{\rho_1\rho_2}{\rho_1 + \rho_2}} . \qquad (20)$$

For dielectric antennas used in practice, with $\epsilon' = 2.5$, the value of ρ_1 is in the range of from 0.5 (for tubes) to 0.85 (for rods).[7] For round rods ρ_2 has a value of 0.7 to 1 (Fradin,[2] p. 514). The concentration of power in dielectric tubes can be judged by the numerical results of Unger,[8] where the damping of the characteristic wave HE_{11} in tubes was found for various values of the ratio of the internal and external radii, including also the case of a continuous rod. One can conclude from those results that for tubes with $\epsilon' = 2.5$ whose wall thickness is 0.1 - 0.2 of the radius, the value of ρ_2 is of the order of 0.1 - 0.2. For such antennas a will have a value of 0.2 - 0.3.

If one takes into consideration the cited estimates of the value of a and formula (18), one can conclude that for tubular antennas the influence of direct radiation of the exciting junction can considerably change the directional pattern in the region of the minor lobes. That influence will be insignificant for rod antennas.

The Influence of the Supplementary Field in the Region of the Exciting Junction

It can be assumed that the supplementary field is localized in the vicinity of the exciting junction, where the characteristic wave of the antenna forms, and decreases with increase of the distance z; to some extent it is analogous to a close field which forms in the direct proximity of heterogeneities in closed waveguides. No data are available on the character of that field. Only in Bobrovnikov's and Smironv's work[9] was the field of a magnetic flux close to a wire over an impedance surface examined, and its damping character was confirmed there. To make clear the qualitative influence of that field on the directional pattern we will approximate the law of its distribution along the Z-axis with the expression

$$f'(z') = be^{-\beta z' - jk_1 z'} . \tag{21}$$

If we neglect the influence of direct radiation of the exciting transition, then after uncomplicated transformations we obtain for the square of the array factor of expression (9)

$$\Psi_2^2(\Theta) = \left(\frac{\sin\alpha}{\alpha}\right)^2 + \frac{b}{a}\, e^{-\beta L/2}\, \frac{ch^2\beta \sin^2\alpha_1 + sh^2\beta \cos\alpha_1}{\alpha_1^2 + \beta_2}$$

$$\cos\left[\psi + \alpha_1 - \alpha + \text{arc tg}\frac{\beta}{\alpha_1} - \text{arc tg}(\text{th}\,\beta\,\text{cth}\,\alpha_1)\right], \tag{22}$$

where

$$\alpha_1 = \pi N\left(\frac{k_1}{k} - \cos\Theta\right).$$

Here the second term, expressing the influence of the supplementary field, depends on its amplitude and rate of decay. It introduces substantial changes in the region of the minor lobes. Its influence can explain the absence of zeros in the directional patterns of real antennas. For tubular antennas that influence will be insignificant on account of the low concentration of the field in the dielectric. It will be most substantial for short and thick rod antennas. It is known from Fradin[2] that in that case a very substantial divergence is observed between experiment and calculations based on the model of a linear traveling-wave antenna.

It should be noted that the qualitative conclusions do not change if one adopts a law of the type of $be^{-\beta z'}$ instead of (21). A more precise analysis of the influence of the supplementary field is impossible at the present time, as no more detailed theoretical or experimental information about its character is available.

The Influence of Processes at the End of the Antenna

In relation to the characteristic wave of a dielectric waveguide the end of the antenna is heterogeneous. The reflection coefficient obtained for it is small,[2,10] and its influence on the directional pattern ought to be expressed mainly in the form of reverse radiation, which is not observed. Therefore, its influence can be considered to be insignificant.

The Influence of an Ideally Conducting Screen

If we take $\vec{E}_1$ and $\vec{H}_1$ in the form of (7) and (8) we have neglected the influence of the screen. With consideration of it, instead of (7) it is necessary to write

$$\vec{E}_1 = -\vec{e}_x \frac{60\pi}{\lambda r}\left(e^{jkz\cos\Theta} - e^{-jkz\cos\Theta}\right). \tag{23}$$

Then in the array factor of expression (9) one must add the term

$$F_4 = -e^{-j\alpha_2}\frac{\sin\alpha_2}{\alpha_2}, \tag{24}$$

where

$$\alpha_2 = \pi N(\xi + \cos\Theta) , \tag{25}$$

and also the corresponding additional terms to $F_2(\Theta)$, which are obtained by the replacement of α by α_2 in those terms. Term (24) will exert a basic influence on the array factor. Its role can be estimated qualitatively by making use of a generalized directional pattern of a linear traveling-wave antenna (Figure 2). On that graph the real directional pattern occupies the region from

$$\alpha_{min} = \pi N(\xi - 1) ,$$

$(\Theta = 0°)$ to

$$\alpha_{max} = \pi N(\xi + 1) .$$

$(\Theta = 180°)$ and can be obtained from Figure 2 by graphical constructions.[5] The term F_4 occupies the region from α_{max} (which corresponds to $\Theta = 0°$) to $\alpha_1(\Theta = 90°)$ and influences mainly the most distant minor lobes.

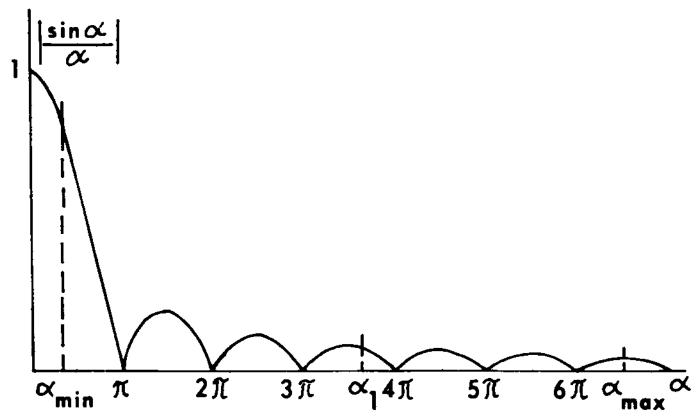

Figure 2

For an antenna without a screen, instead of its influence it is necessary to take into consideration the field created by the currents passing over the external surface of the exciting metallic waveguide. It can be expected that that influence will be perceptible only in the region of the most distant minor lobes.

Conical Dielectric Antennas

For approximate analysis of the properties of a conical antenna one can use an expression obtained by Sengupta[11] for the directional pattern of a linear traveling-wave antenna whose propagation constant varies linearly and fairly slowly along the axis of the antenna

$$F^2(\Theta) = \left(\frac{\sin\alpha}{\alpha}\right)^2 + \left[\frac{1}{4}\frac{\Delta k_a}{k_{a\,av}}\left(1 + \frac{2\pi N}{\alpha}\right)\frac{\cos\alpha}{\alpha}\right]^2 , \qquad (26)$$

where

$$\alpha = \pi N(\xi_{av} - \cos\Theta) ,$$

$$k_{av} = \frac{k_1 + k_2}{2} ,$$

$$\Delta k_a = k_1 - k_2 ,$$

and k_1 and k_2 are the propagation constants at the beginning and end of the antenna.

Let us draw a graphic interpretation of that formula, using generalized directional patterns. On Figure 3 are curves 1 and 2 corresponding to the first and second terms of expression (26). The second term does not change the absolute level of the first minor lobe. If the relative antenna length is selected in accordance with the condition of obtaining a maximum amplification factor for an antenna homogeneous along its length, for which $k_a = k_{a\,av}$[12]

$$\frac{k_{a\,av}}{k} = 1 + \frac{1}{2N} , \qquad (27)$$

then that corresponds to $\alpha_{min} = \pi/2$ and the directional pattern of such an antenna will have no advantages. However, the antenna parameters are so selected that a lowering of the level of the minor lobes can be obtained by increasing the absolute level of the major lobe. This fact can be considered the main advantage of conical antennas.

Conclusion

The analysis of the influence of supplementary factors on the directional

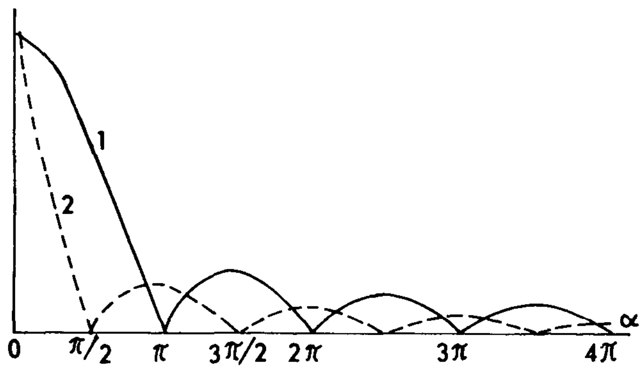

Figure 3

pattern of a dielectric antenna that has been made and was represented in first approximation in the form of (19) shows that the properties of the excited transition have a substantial influence on the directional pattern only of fairly short antennas. For long antennas, among which one can include piecewise linear antennas,[13] antennas with modulation of the dielectric constant[14,16] and also long thin tubes with a spiral exciter,[16] that influence will have a ngeligible value.

The examination was conducted by means of a number of parameters (a, ψ, b, and β) characterizing the field in an antenna. Precise determination of them will become possible only when the problems of excitation of dielectric rods and tubes with a wave HE_{11} have been solved and the character of the field in the region of the exciting junction has been investigated.

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Infinite dielectric waveguide						
Integral equations						
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