TELECOMMUNICATIONS

AND RADIO ENGINEERING

Volume **60, 2003** Numbers 7, 8 and 9

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MICROWAVE ELECTRODYNAMICS

ANTENNAS AND FEEDER SYSTEMS

TELECOMMUNICATIONS AND RADIO ENGINEERING (ISSN 0040-2508)

TELECOMMUNICATIONS AND RADIO ENGINEERING (ISSN 0040-2508) is a translation (from Russian into English) journal comprised of selected papers from *Radio Physics and Radio Astronomy*, ISSN 1027-9636, *Radio Physics and Electronics*, ISSN 1028-821X and *Radio-Engineering*, ISSN 0485-8972. The original papers will also be published, especially if they review seminar articles that have never appeared in Western literature. Subjects covered in *Telecommunications and Radio Engineering* include, but are not limited to: digital and analog communications, micro- and millimeter-wave communications; switching and coding theory; signal processing; micro-millimeter and sub-millimeter engineering; antennas; waveguides; electron, solid-state, and quantum devices; radio wave propagation and investigation of surrounding environment; radio astronomy; applied radio physics and industrial electronics; radar and radio navigation engineering; and theory of microwave systems.

TELECOMMUNICATIONS AND RADIO ENGINEERING ™(ISSN 0040-2508) is published monthly and owned by Begell House, Inc., 145 Madison Avenue, New York, NY 10016, telephone (212) 725-1999. In 2003 two volumes of this journal are being published at a price $3,357.00 for both volumes. Add $10.00 per issue for airmail service outside the United States and Canada. All subscription are payable in advance. Subscriptions are entered on an annual basis, i.e., January to December. Orders should be sent to Begell House, Inc. 145 Madison Avenue, New York, NY 10016. Payments should be made by dollar checks drawn on a U.S. bank.

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3. The mutually consistent spatial phase-and-frequency control of radiation focusing that has been suggested here for continuous and pulsed signals in the channels of a planar, equally-spaced phased antenna array (Eqs. (4) and (5)) is easily implementable technically with the use of commercially available narrow-band microwave units.
4. A mathematical model has been developed to analyze the effect of an additional spatial control of phases on the space-and-time pulse focused in the Fresnel zone. The results have shown that application of a consistent spatial control of phases and frequencies with a discrete V-shaped distribution of the carrier frequencies over the array aperture allows generating a focused space-and-time pulse already in the Fresnel zone at ranges $Z_F \geq 0.1 Z_d$.
5. The use of a symmetric discrete V-shaped distribution of the carrier frequencies over the array aperture excited by continuous signals makes it possible to form a train of short high-power, localized r.f. pulses whole parameters are determined by Eqs. (7) to (9) in the absence of scanning.

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Electromagnetic Wave Diffraction by a Cone with Longitudinal Slots and a Solid Conic Screen Inside*

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A numerical-analytical solution of the problem of exitation of an unlimited perfectly conducting biconical surface is considered. Surface consists of both a cone with periodical longitudinal slots and an internal solid conical screen. The effects of slots and solid cone on the Fourier coefficient of the electromagnetic field components and the scattering patterns are discussed. The obtained results are in good agreement with previously recognized ones for solid bicone structure.

Introduction

The boundary electromagnetic problems for non-closed conic and biconic structures find their immediate application while designing wide-band and superwide-band antenna systems [1]. The electromagnetic characteristics and directional radiation can be easily controlled due to the surface inhomogeneities, e.g. slots at the scattering surface. The authors of [2] have suggested an approach to determining the Green function of the second boundary-value problem of the Helmholtz equation for a semi-infinite circular thin cone with periodical longitudinal slots, parallel to the moving lines, and obtained a solution in the extreme case of a semi-transparent cone. This approach has been applied to electromagnetic boundary problems for a cone with longitudinal slots [3-5] and extended to the problems of wave scattering by biconic surfaces [6, 7]. In [7], a rigorous analytical solution was found to the problem considering a cone with periodical longitudinal slots and a solid cone inside excited by a magnetic radial dipole, in a special case of multiple slots having the width smaller than the period. This solution served as a ground for studying the effect of slots and a solid conic screen upon the spectrum of a boundary problem, field structure and its behavior close to the vertex. The aim of this study is to develop a numerical algorithm to be validated in numerical experiments with random parameters.

Problem statement. Solution technique

Consider a case of a semi-infinite thin circular perfectly conducting cone with a periodical longitudinal N slots with a semi-infinite thin circular solid cone inside, with coinciding vertexes and axes of the cones, exposed to the radiation of a radial dipole (Fig.1). Assume that the dipole field situated at the point B_0 and the moment $\vec{p}$ directed to the vertex, varies harmonically in time. Since the cone coincides with one of the coordinate surfaces of the spherical coordinates r, θ, φ, we can assign the cone vertex to be the origin. In these coordinates, the solid cone Σ_1 is determined by the equation $\theta = \gamma_1$, and a cone with longitudinal slots Σ_2 by the equation $\theta = \gamma_2$, where r_0, θ_0, φ_0 are the source coordinates.

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* Originally published in *Radiotechnika*, No 131, 2003, pp. 71–75.

ISSN0040-2508

The slot width d_2 and the period $l = 2\pi/N$ of the cone Σ_2 are the values of the dihedral angles constituted by intersection of planes crossing the cosine axis and ribs of the neighbor conic strips. The electromagnetic field $\vec{E}, \vec{H}$ in a medium having a bicone $\Sigma = \Sigma_1 \bigcup \Sigma_2$ and the source, satisfies the set of the Maxwell equations, the boundary condition of a vanishing tangential electric component at the surface of bicone Σ, the infinity condition and the energy boundedness condition.

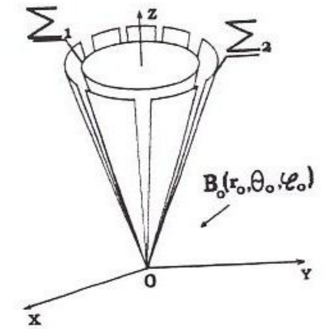

Fig. 1.

Such a statement of the electromagnetic problem has a unique solution [8]. Present $\vec{E}$ and $\vec{H}$ in the form

$$\vec{E} = \vec{E}_0 + \vec{E}_1 \text{ and } \vec{H} = \vec{H}_0 + \vec{H}_1 \tag{1}$$

where $\vec{E}_0, \vec{H}_0$ is the dipole field, $\vec{E}_1, \vec{H}_1$ is a field scattered by the bicone Σ. The solution to the electromagnetic problem utilizes the magnetic Debye potential $\upsilon(r,\theta,\varphi)$, which is used to express the components of the electromagnetic field $\vec{E}, \vec{H}$ in terms of

$$E_r = 0, \qquad H_r = \left(\frac{\partial^2}{\partial r^2} - q^2\right)\cdot(r\upsilon),$$

$$E_\theta = -\frac{qw}{\sin\theta}\cdot\frac{\partial}{\partial\varphi}\upsilon, \qquad H_\theta = \frac{1}{r}\cdot\frac{\partial^2}{\partial r\partial\theta}\cdot(r\upsilon), \tag{2}$$

$$E_\varphi = qw\frac{\partial}{\partial\theta}\upsilon, \qquad H_\varphi = \frac{1}{r\sin\theta}\cdot\frac{\partial^2}{\partial r\partial\varphi}\cdot(r\upsilon),$$

where $q = -ik$ ($\operatorname{Im} k \ge 0$), k is the wave number, when the harmonic time dependence t is written as $\exp(i\omega t)$, $q = ik$ ($\operatorname{Im} k \le 0$) by the harmonic time dependence t in the form $\exp(-i\omega t)$, $w = \sqrt{\mu/\varepsilon}$ is the wave resistance of the medium with the dielectric ε and magnetic μ permittivities. The sought a Debye potential υ satisfied

1) the homogeneous Helmholtz equation $\Delta\upsilon - q^2\upsilon = 0$ outside the bicone and the source,
2) the Neimann boundary condition at the bicone surface:

$$\frac{\partial\upsilon}{\partial n}\Big|_\Sigma = 0; \tag{3}$$

3) the principle of limit absorption,
4) the energy boundedness condition.

In accordance with the complete field structure (1) υ sought the Debye potential of the dipole field in the form

$$\upsilon = \upsilon_0 + \upsilon_1, \quad \upsilon_0 = b_0\frac{e^{-q|\vec{r}-\vec{r}_0|}}{4\pi|\vec{r}-\vec{r}_0|},$$

and $\upsilon_1(r,\theta,\varphi)$ is the potential for the scattered field, $b_0 = -\dfrac{w|\vec{p}|}{qr_0}$.

One of the efficient tools for solving boundary problems with a conical boundary are the Kontorovich-Lebedev integral transforms [9, 1-3, 10]. The unknown potential υ_1 will then be sought in from of the Kontorovich-Lebedev integral with respect to the radial coordinate of the spherical coordinates

$$\upsilon_1 = \frac{2}{\pi^2}\int_0^\infty \tau sh\pi\tau\bar{\upsilon}_1\frac{K_{i\tau}(qr)}{\sqrt{r}}d\tau, \quad \bar{\upsilon}_1 = \int_0^\infty \upsilon_1\frac{K_{i\tau}(qr)}{\sqrt{r}}d\tau,$$

$$\bar{\upsilon}_1 = -\sum_{m=-\infty}^{+\infty} a_{m\tau}U_{m\tau}(\theta,\varphi)P_{-1/2-i\tau}^m(-\cos\theta_0)\frac{d}{d\gamma_2}P_{-1/2+i\tau}^m(\cos\gamma_2),$$

$$U_{m\tau} = \begin{cases} \sum\limits_{n=-\infty}^{+\infty}\left[\beta_{mn}P_{-1/2+i\tau}^{m+nN}(\cos\theta) + \xi_{mn}P_{-1/2+i\tau}^{m+nN}(-\cos\theta)\right]e^{i(m+nN)\varphi}, & \gamma_1 < \theta < \gamma_2, \\ \sum\limits_{n=-\infty}^{+\infty}\eta_{mn}P_{-1/2+i\tau}^{m+nN}(-\cos\theta)e^{i(m+nN)\varphi}, & \gamma_2 < \theta < \pi, \end{cases}$$

where $K_\varsigma(z)$ is the MacDonald function, $\Gamma(z)$ is the gamma-function, $P_\varsigma^m(\cos\theta)$ – is the associated Legendre function of the first kind, $\beta_{mn}, \xi_{mn}, \eta_{mn}$ – are the sought coefficients. Suppose that the source lays beyond the cone Σ_2 ($\gamma_2 < \theta_0$). The relation between the unknown coefficients and the functional equations for determining them are obtained from the field continuity condition (the Debye potential and its partial derivatives) in slots and boundary conditions (3) at solid cone Σ_1 and strips of cone Σ_2. As a result, we arrive at the set of functional equations with respect to the unknown coefficients $y_n^{(m_0)}$, which are used to express the sought coefficients [7]:

$$\sum_{n=-\infty}^{+\infty} y_n^{(m_0)} e^{inN\varphi} = 0, \qquad \pi d/l < |N\varphi| \le \pi, \tag{4}$$

$$\sum_{m=-\infty}^{+\infty} \frac{1}{N(n+\nu)} \frac{|n|}{n}(1-\varepsilon_n) y_n^{(m_0)} e^{inN\varphi} = -\frac{1}{N(m_0+\nu)} g_\tau^{(m_0)} e^{im_0 N\varphi}, \qquad |N\varphi| < \pi d/l, \tag{5}$$

$$g_\tau^{(n)} = \frac{|n|}{n}(1-\varepsilon_n)(1-C_\tau^{(n+\nu)N}),$$

$$C_\tau^M = \frac{\frac{d}{d\gamma_1} P^M_{-1/2+i\tau}(\cos\gamma_1) \frac{d}{d\gamma_2} P^M_{-1/2+i\tau}(-\cos\gamma_2)}{\frac{d}{d\gamma_1} P^M_{-1/2+i\tau}(-\cos\gamma_1) \frac{d}{d\gamma_2} P^M_{-1/2+i\tau}(\cos\gamma_2)},$$

$$\delta_n^{m_0} = 1, n = m_0, \quad \delta_n^{m_0} = 0, n \ne m_0,$$

$$\frac{1}{N(n+\nu)} \frac{|n|}{n}(1-\varepsilon_n) = \frac{(-1)^{(n+\nu)N+1} ch\pi\tau}{\pi \sin^2\gamma_2} \frac{\Gamma(1/2+i\tau+(n+\nu)N)}{\Gamma(1/2+i\tau-(n+\nu)N)} \times$$

$$\times \frac{1}{\frac{d}{d\gamma_2} P^{(n+\nu)N}_{-1/2+i\tau}(\cos\gamma_2) \frac{d}{d\gamma_2} P^{(n+\nu)N}_{-1/2+i\tau}(-\cos\gamma_2)} \frac{1}{1-C_\tau^{(n+\nu)*N}}.$$

$\frac{m}{N} = m_0 + \nu, m_0$ is the next integer to $\frac{m}{N}$, $-1/2 \le \nu < 1/2$. For the coefficients ε_n, at $(n+\nu)N >> 1$, holds $\varepsilon_n = O\left(\frac{1}{(n+\nu)^2 N^2}\right)$.

Applying the regularization manipulation to eqs. (4), (5) and the method of the Riemann-Hilbert problem [2, 7], reduce the initial problem to the solution of a set of the Fredholm linear algebraic equations of the second kind (SLAE-2) with respect to the coefficients $x_n^{m_0} = y_n^{m_0} + \delta_n^{m_0}$ of the form:

$$x_n^{m_0} - \delta_n^{m_0} = \sum_{p=-\infty}^{+\infty} b_{np}(x_p^{m_0} - \delta_p^{m_0}) - g_\tau^{(m_0)} V_{n-1}^{m_0-1}(u), \qquad n = 0, \pm 1, \pm 2, \ldots \tag{6}$$

$$M_\nu(-u)(x_0^{m_0} - \delta_0^{m_0}) = N \cdot \nu \sum_{p=-\infty}^{+\infty} \left[\frac{|n|}{n} \varepsilon_n (x_0^{m_0} - \delta_0^{m_0}) - g_\tau^{(n)} \delta_n^{m_0}\right] V^p(u). \tag{7}$$

$$b_{np} = \frac{|p|}{p} \varepsilon_p V_{n-1}^{m_0-1}(u) + \delta_p^{o} P_n(u), u = \cos\alpha, \quad \alpha = \pi d/l,$$

$$V_{n-1}^{p-1}(u) = \frac{n}{2(n-p)}[P_{n-1}(u)P_p(u) - P_n(u)P_{p=1}(u)], n \ne p,$$

$$V^p(u) = \frac{1}{p+\nu}\{P_p(u) + M_\nu(-u)V_{p-1}^{-1}(u)\}, \quad V_{n-1}^{-1}(u) = \frac{1}{2}[P_{n-1}(u) - P_n(u)],$$

$$M_\nu(u) = \frac{2P_{\nu-1}(u)}{P_\nu(u) + P_{\nu-1}(u)}.$$

It should be noted that the matrix coefficients SLAE-2 do not depend on the wave number k, which essentially simplifies the algorithm of constructing the scattering diagrams and determining the field near the bicone vertex. The solution for SLAE-2, regardless of the parameters, can be found numerically by using the reduction method. Thus, this method is chosen to be used for the numerical solution to the stated problem.

Numerical solution

Consider a case where the source is situated at an axis of a biconical structure ($m = m_0 = 0, \nu = 0$), and the cone Σ_2 has a single slot ($N = 1$). The absolute values of the coefficients x_n, which are the solution to the set (6), (7), never exceed a unit. Figs. 2, and 3 demonstrate the relations $|x_n|, n = 0, 1$ between the slot width d_2 and various fixed opening angles of the solid cone $\theta = \gamma_1$ ($\gamma_2 = \pi/8$, 1. - $\gamma_1 = \pi/18$, 2. - $\gamma_1 = \pi/16$, 3. - $\gamma_1 = \pi/14$.).

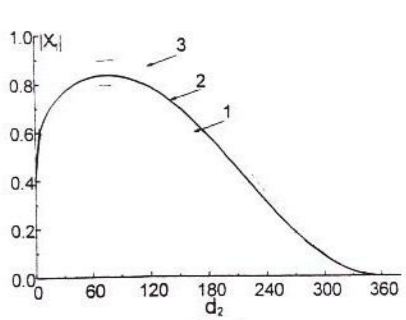

Fig. 2

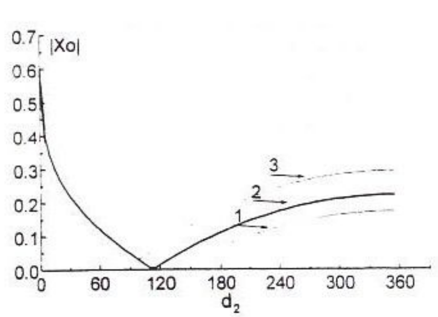

Fig. 3

The coefficient x_0 depends on the field reflection from the biconical surface and in the extreme, slot-free, case ($d_2 = 0$) is equal to a unit (solid cone $\theta = \gamma_2$). As the slot width grows, the coefficient $|x_0|$ decreases down to zero (the minimum), and then increases again (Fig.2). When the opening angle of the solid cone $\theta = \gamma_1$ is becoming smaller, the minimum $|x_0|$ moves toward widening of the slot d_2. For a narrow solid cone ($\gamma_1 << 1$) the curve featuring the relation $|x_0|$ vs. d_2 replicates the curve $|x_0|$ for a solid cone with a longitudinal slot [11]. The rest of the coefficients depend on the field penetrating through the slot into the space between cones Σ_1 and Σ_2 and decrease as the width of the slot and the conical strip narrows. The curve of dependence between $|x_1|$ and the slot width is shown in Fig.3. As the slot widens, $|x_1|$ shows a monotone increase followed by a decrease to zero. In the vicinity of $d_2 = 70^0$, $|x_1|$ reaches its maximum over the whole width variation interval. The field in the far zone is determined from the presentation (2) of the electromagnetic field components via the Debye potential and the behavior of the MacDonald function $K_\zeta(z)$ if $z >> 1$ [12]. Figs.4, 5 present the field scattering patterns in the horizontal plane, normal to the structure axis, for various slot widths ($\gamma_1 = \pi/16, \gamma_2 = \pi/8, \theta = \pi/4 + \pi/20, kr_0 = 1$, Figure 4: 1. – $d_2 = 5^0$, 2. – $d_2 = 30^0$, 3. –$d_2 = 60^0$; Fig.5: 1. – $d_2 = 90^0$, 2. – $d_2 = 180^0$, 3. –$d_2 = 240^0$).

Analyzing the scattering patterns, one can conclude that the wider the slot width, the more pronounced the influence of the internal solid cone on the radiation from the slot. The peak radiation is observed by the slot width of 60° (Fig.4). As the slot widens, thus the angular dimension of the conical strip shrink, the pattern changes continuously, becoming a circular one, for the case of biconical surface – solid cone Σ_1).

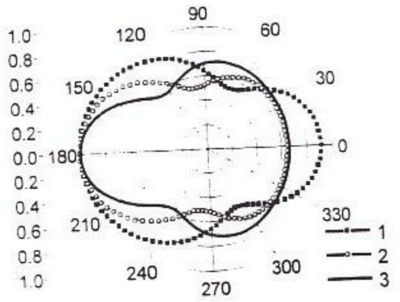

Fig. 4.

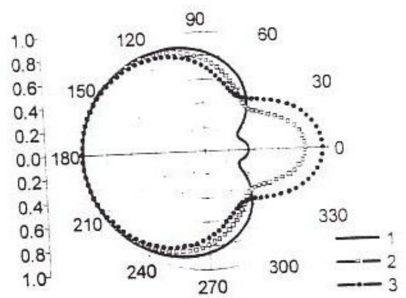

Fig. 5.

Conclusion

The result of the study is a numerical analytical algorithm for solving the problem of an unlimited perfectly conducting biconical surface consisting of a cone with periodical longitudinal slots and an internal solid conical screen, excited by a magnetic radial dipole. A numerical solution has been found, which served as a basis for analyzing the effect exerted by slots and the solid cone on the Fourier coefficients of the electromagnetic field components and the scattering patterns. In the extreme cases of the biconical structure, the obtained results were in good agreement with the formerly reported ones for a solid cone and a bicone.

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