ISSN 1064-2269, Journal of Communications Technology and Electronics, 2013, Vol. 58, No. 7, pp. 691–694.

ELECTRODYNAMICS AND WAVE PROPAGATION

The Effect of Subwavelength Localization of the Electromagnetic Field on the Surface of a Circular Metamaterial Cylinder

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Received January 29, 2013

Abstract—The 2D problem of excitation of a circular metamaterial cylinder by a filamentary source is numerically investigated. It is found that, for the minus one values of the relative permittivity and permeability, the field on the surface of the cylinder concentrates in a region that is located on the illuminated surface of the cylinder and that is small compared to the wavelength.

DOI: 10.1134/S1064226913070024

Electrodynamic objects made from a material that is characterized by minus one relative permittivity ε and minus one relative permeability μ exhibit extraordinary properties. Thus, from the point of view of geometric optics, a plane-parallel plate is an ideal lens where there are no geometric aberrations and rays pass through the medium interfaces without reflection [1]. A rectangular prism can serve as a corner reflector in which the beam twice refracts on the faces of the prism and returns to the source [2].

In this study, the 2D problem of diffraction of a cylindrical wave by a circular cylinder is considered in the situation when the cylinder is made from a material with the parameters

$$\varepsilon = \mu = -1. \quad (1)$$

We investigate the case of the TM polarization, when the electromagnetic field has components $H_z(x, y)$, $E_x(x, y)$, and $E_y(x, y)$. The diffraction problem is reduced in this case to finding scalar function $U(x, y) = H_z(x, y)$, that satisfies the Helmholtz equation both inside and outside the cylinder, the corresponding boundary conditions on the surface of the cylinder $r = a$, and the radiation condition at infinity. Incident field $U_0(r, \varphi)$ is specified as

$$U_0(r,\varphi) = H_0^{(2)}\left(k\sqrt{r^2 + r_0^2 - 2rr_0\cos(\varphi - \varphi_0)}\right), \quad (2)$$

where $H_0^{(2)}$ is the Hankel function, k is wave number in free space, (r, φ) and (r_0, φ_0) are the polar coordinates of the observation point and the source, respectively. The time dependence of the fields is described by the factor $\exp(i\omega t)$. Below, we assume that $\varphi_0 = -\pi/2$ (Fig. 1).

The modified method of discrete sources is used for the numerical solution of the problem formulated above [3, 4]. This method was applied to solve problems of diffraction by electrically large cylinders in [5]. In this study, we consider only the cylinders whose dimensions are smaller than the wavelength $\lambda = 2\pi/k$.

Figure 2 shows the absolute value of total field $U(a, \varphi)$ on the cylinder surface as a function of the arc

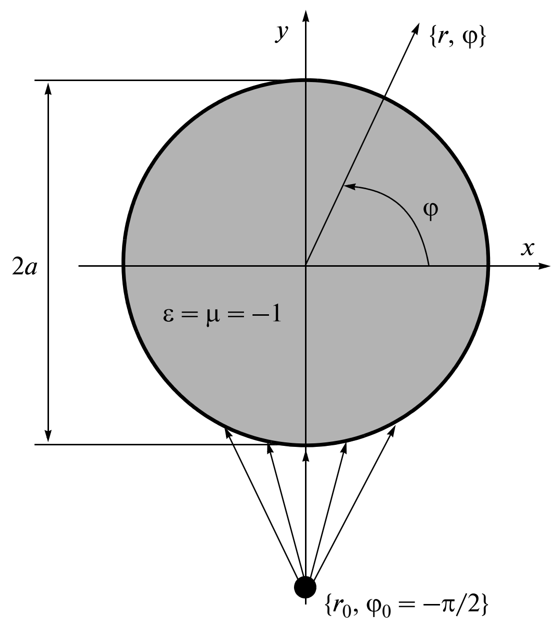

Fig. 1. Geometry of the problem.

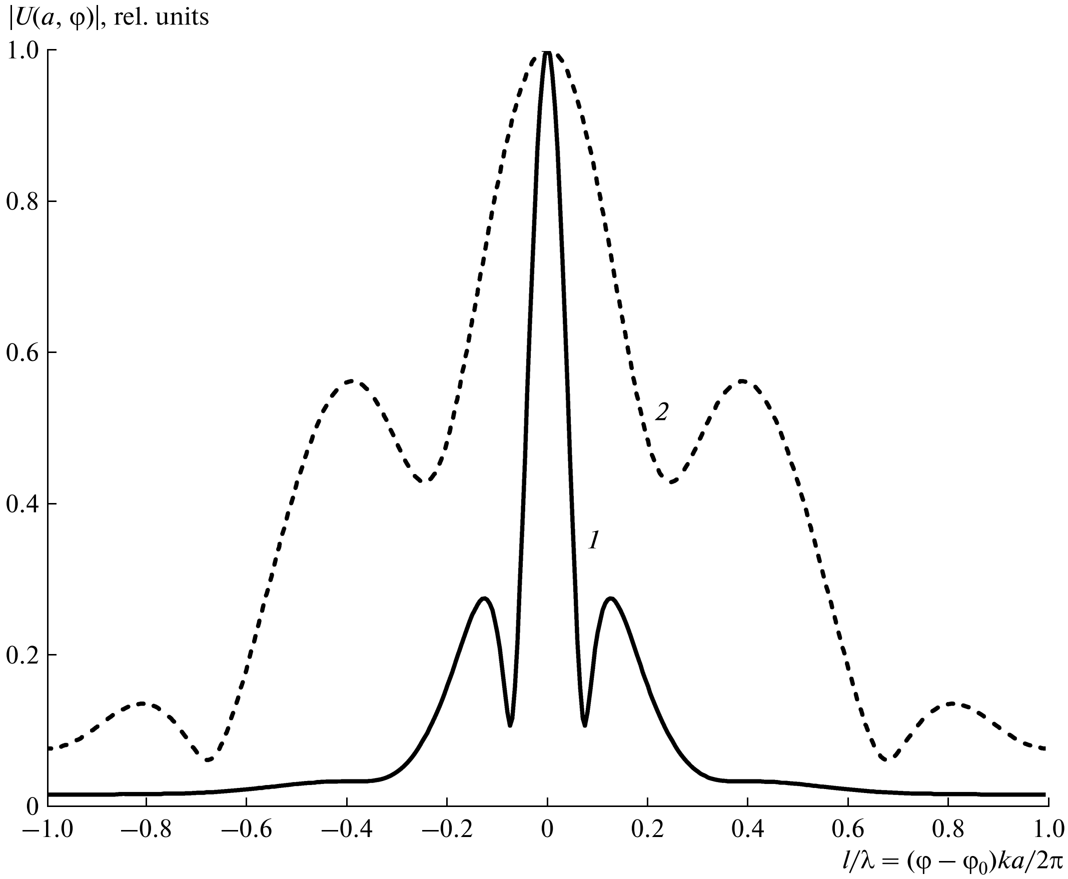

Fig. 2. Absolute value of the total field on the cylinder's surface vs. the arc length at $ka = 2$. Curves *1* and *2* correspond to $kr_0 = 3$ and $kr_0 = 50$, respectively.

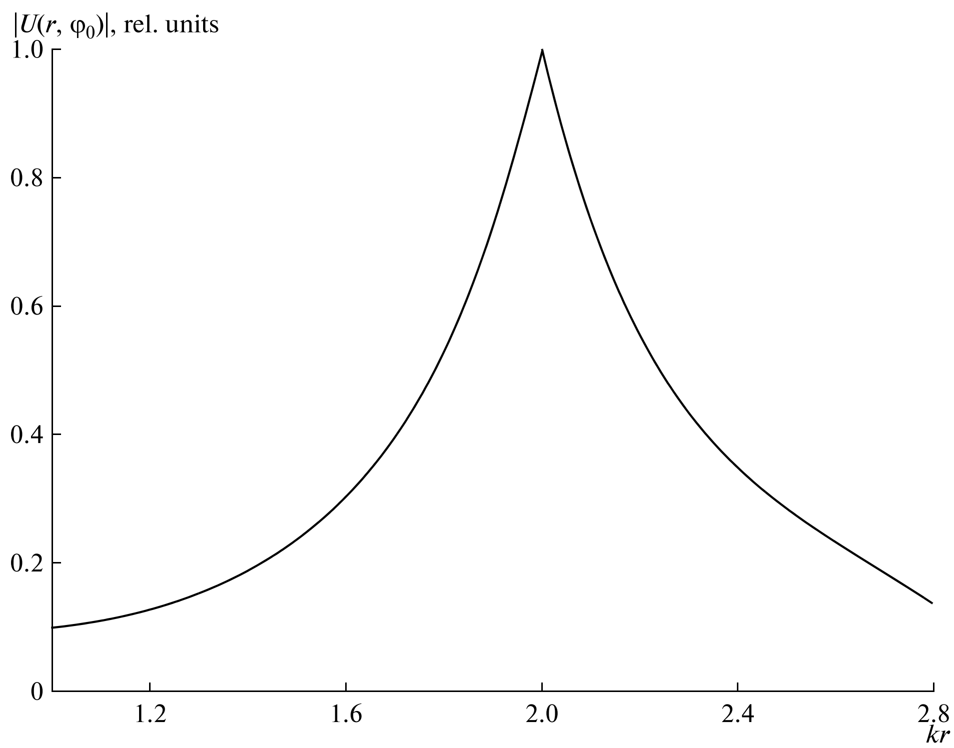

Fig. 3. Absolute value of total field $|U(r, \varphi_0)|$ vs. the radius at $ka = 2$ and $kr_0 = 3$.

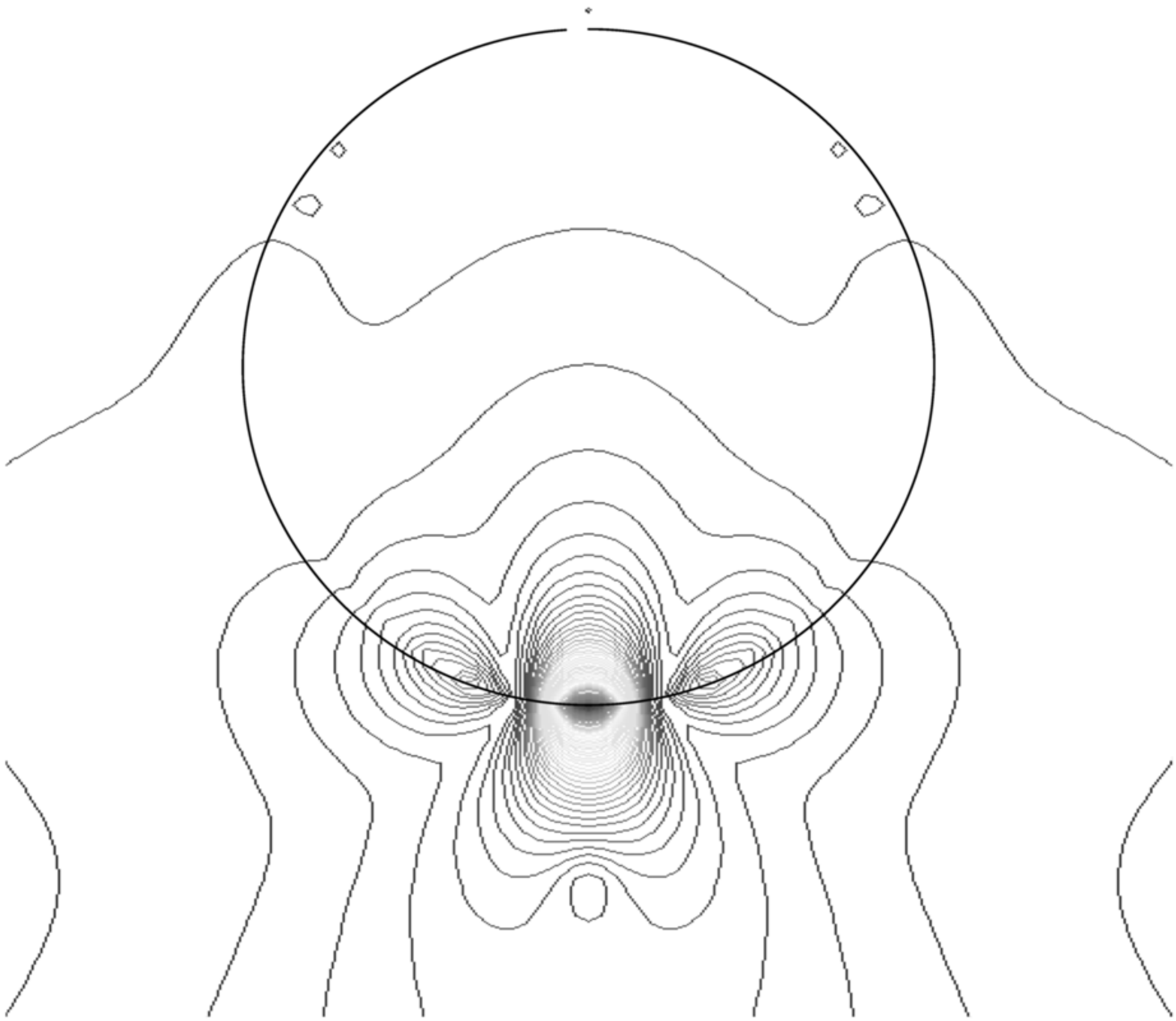

Fig. 4. Constant-level lines of function $|U(r, \varphi)|$ at $ka = 2$ and $kr_0 = 3$.

length $l = a(\varphi - \varphi_0) = \dfrac{ka(\varphi - \varphi_0)\lambda}{2\pi}$ for the case $ka = 2$. Curves *1* and *2* correspond to two different positions of the source: $kr_0 = 3$ and $kr_0 = 50$. It is seen from the figure that the field localizes near the direction $\varphi = \varphi_0$. The linear dimension of the spot is approximately $\lambda/10$ for $kr_0 = 3$ and $\lambda/2$ for the case $kr_0 = 50$, which practically corresponds to the problem of diffraction of a plane wave. Thus, the effect of subwavelength field localization is realized only when the distance between the source and the surface of the cylinder is small compared to the wavelength.

It is important to note that the field localizes at the point $r = a$, $\varphi = \varphi_0$ not only in angular coordinate φ but also in radial coordinate r. The graph of function $|U(r, \varphi_0)|$ is depicted in Fig. 3 for the case $ka = 2$, $kr_0 = 3$. It is seen that the field concentrates in a narrow region near the surface of the cylinder $r = a$. Such behavior of the field is typical of surface waves propagating along the interface. The spatial distribution of the absolute value of the total field is illustrated in Fig. 4, which shows constant-level lines of function $|U(r, \varphi)|$.

The distribution of the absolute value of the field on the surface of the cylinder is displayed in Fig. 5 for $ka = 6$, and $kr_0 = 7$. It follows from the comparison of Figs. 2 and 5 that, in the case of a threefold increase in the diameter of the cylinder, the interference pattern is qualitatively retained and the width of the main lobe has also the same order $\lambda/10$.

Thus, in the neighborhood of the point $r = a$, $\varphi = \varphi_0$ the wave field spatially localizes in a region whose linear dimensions are much smaller than λ.

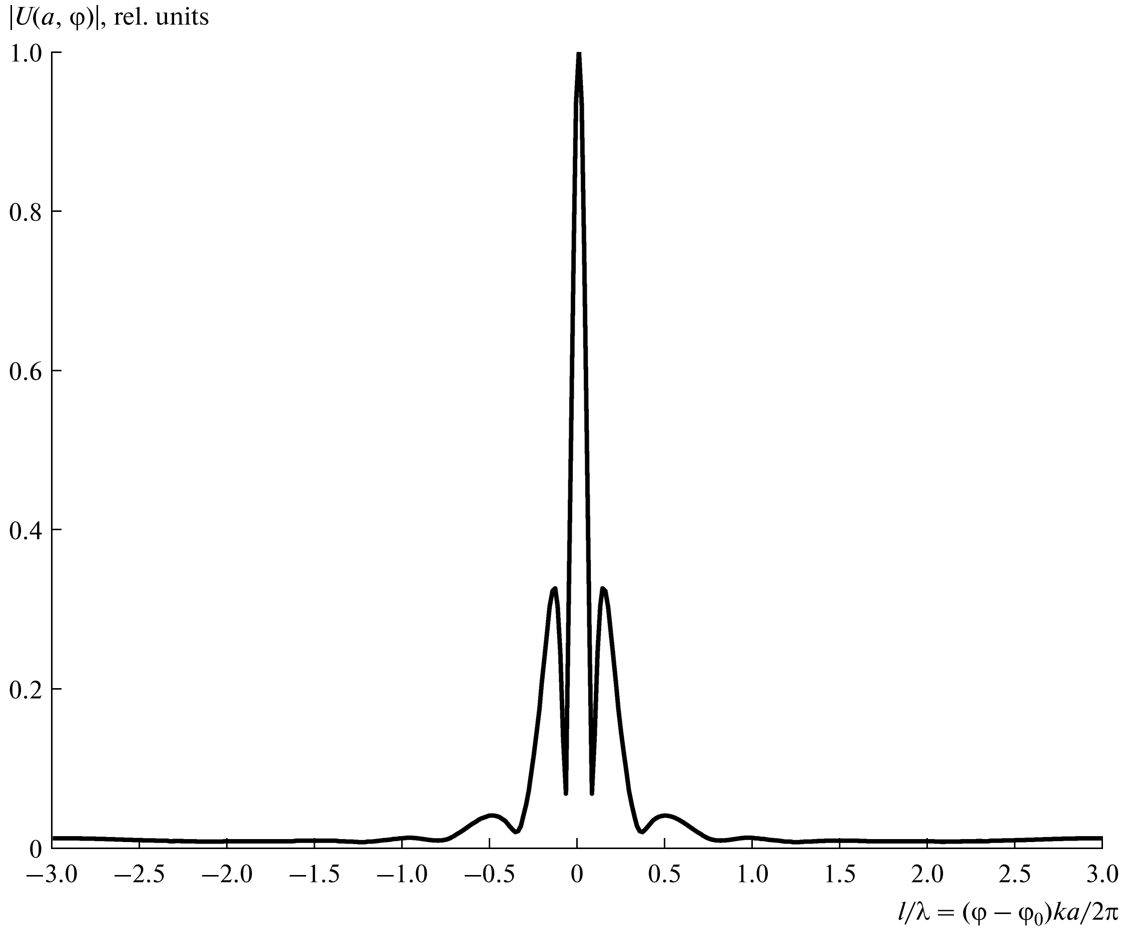

Fig. 5. Constant-level lines of the total field on the cylinder's surface vs. the arc length at $ka = 6$ and $kr_0 = 7$.

We can suppose that subwavelength spatial localization of the field is realized due to the interference of very slow surface waves propagating along the boundary of the cylinder. It is known that, on the plane boundary of a half-space filled by medium (1), there exist surface waves with arbitrarily large slowing factors, and these waves form a continuous spectrum [6]. It is obvious that the curved boundary $r = a$ can approximately be regarded as a plane one for waves with a large slowing factor.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research, project no. 12-02-00062-a.

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Translated by A. Vyazovtsev