Dynamic Behavior of Dielectric Antennas at High Communication Rates

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Abstract: - Broadband wireless technology for future second generation macro-cellular non-line-of-sight architecture is globally emerging as the viable alternative to wired technology for meeting high speed data demands of the increasing residential and small business customers. Miniaturization and efficiency of the multiple antennas that utilize spatial diversity schemes, on the indoors CPE side, play a very important role in efficiently capturing the multipath signals in a rich scattered environment to combat fading and enhance system throughput. This paper introduces some baseline results of dielectric loaded antennas that would be potential for meeting high data rate specifications for future CPEs. Dielectrically loaded antennas are small, protected from damages and easily controlled. Stationary operation of a dielectric antenna can be computed using standard methods, but those methods meet big difficulties in dynamic problems. The generalized eigenfunction method applied earlier to diffraction problems and in laser theory can help to find within a reasonably limited amount of calculation not only static but dynamic characteristics of antennas. The dynamic analysis is important for estimation of the maximum information rate which can be transmitted through the antenna without distortion. Presented pictures show examples of dynamic changes in antenna pattern and in input impedance for different cylindrical dielectric antennas with a step excitation.

Keywords: - Dielectric, cylindrical antennas, eigenfunction, dynamic behavior, high data rates

1 INTRODUCTION

Dielectrically loaded antennas are small, protected from damages and easily controlled. Stationary operation of a dielectric antenna can be computed using standard methods, but those methods meet big difficulties in dynamic problems. The generalized eigenfunction method applied earlier to diffraction problems and in laser theory can help to find within a reasonably limited amount of calculation not only static but dynamic characteristics of antennas. The dynamic analysis is important for estimation of the maximum information rate which can be transmitted through the antenna without distortion. Presented pictures show examples of dynamic changes in antenna pattern and in input impedance for a short cylindrical dielectric antenna with a step excitation.

For the analysis of dielectric resonators fields are expanded in the series of eigenfunctions or eigenmodes. The method is particularly effective if the frequency of operation is close to one of the resonant eigenvalues and the resulting field is close to one of the modes. This so-called frequency method can be applied to radiative resonators like dielectric antennas, but the integration over continuous spectrum of radiative modes makes calculations difficult even for a stationary operation.

Partially this difficulty can be overcome by using the generalized eigenfunction method
, developed for diffraction problems[1] and the theory of lasers [2]. In this method not the frequency but some of the system parameters (dielectric permittivity, for example) form the set of eigenvalues, and the eigenfunctions are orthogonal inside the dielectric only. It helps to avoid integration over continuous spectrum at least for the calculation of the fields on the dielectric antenna surface. Outside the dielectric the fields can be always presented as the sum of eigenfunctions plus the source field in the absence of the dielectric (if the source is inside the dielectric, expansion in terms of eigenfunctions is valid even outside the dielectric[1]). Alternatively Kirhoff’s integral can be used for calculation of the antenna pattern. In the present paper we tried both possibilities.

Limited amount of calculations makes it real to solve the dynamic problem of the mode formation after a step function excitation by the source. The dynamic method is described in [2]. Preliminary results for a 2-D problem of an infinitely long cylinder antenna were presented in [3] and [4]. Here we show an example of a 3-D problem – a short dielectric antenna, excited by a thin metal rod, placed at the axis of the cylinder. To simplify the problem, we consider the current distribution along the rod as a given function. Otherwise, a standard method of Green’s functions should be used to find the distribution [5].

2 BOUNDARY PROBLEM

We consider a vertical dielectric cylinder with radius $b$ and height $d$. A metal rod is placed along the central axis of the cylinder with the dielectric permittivity $\varepsilon$. The cylinder is placed on a horizontal conductive plane. Standard boundary conditions—continuity of tangent ional field components are satisfied on the periphery and on the upper face of the cylinder. Radiation conditions are supposed in the infinity, and the fields are limited on the axis of the cylinder. This standard set of boundary conditions is described in multiple books and papers (see, for example, [1,3,4,5,6]).

It is shown in [6] that because of the axial symmetry electromagnetic fields can be described in terms of a single scalar TM-type wave potential $u$, with the magnetic field $H$ expressed through $u$ in the form

$$H(r, z) = j \frac{\varepsilon_0 \varepsilon}{\mu_0} \frac{\partial u}{\partial r}$$

where we accept standard cylindrical coordinates $r$, $z$ and $\varphi$, and standard definitions

$$\varepsilon_0 = 1/(36\pi \times 10^9) \text{F/m}$$
$$\mu_0 = 4\pi \times 10^{-7} \text{H/m}$$

and $\varepsilon$ is the dielectric permittivity, which is equal to 1 outside the dielectric and more than 1 inside it.

The wave potential satisfy the wave equation

$$(\nabla^2 + \varepsilon k^2) u = 0 \quad \text{at} \quad r > 0.$$  

Again $\varepsilon = 1$ outside the dielectric and $\varepsilon > 1$ inside it, and $k$ is the free space wavenumber $(k = \omega / c)$, $\omega$ is the angular frequency of excitation, $c$ is the velocity of light in vacuum.

Eigenfunctions have the form

$$u_q = u_q(z) u_q(r)$$

$$u_q(z) = C_1 \cos(k\sqrt{\varepsilon_n} z) \text{ at } z < d$$
$$u_q(z) = C_2 \exp(jp_i z) \text{ at } z > d$$

$$u_q(r) = C_3 J_m(n_i \sqrt{\varepsilon_n} r) \cos m\varphi \text{ at } r < b$$
$$u_q(r) = C_4 H_m(q_i r) \cos m\varphi \text{ at } r > b$$

where $J$ and $H$ are Bessel and Hankel functions, the constants of normalization $C_{1,2,3,4}$ can be found in [6], and index $q$ is an aggregation of radial index $n$ and angular indices $m$ and $l$ [1].

The set of eigenfunction is received incorporating all the boundary conditions, and the eigenvalues $\varepsilon_n$ are found together with the parameters $q, p, n$ from the system of equations.
\[ k_i^2 + q_i^2 = k^2 \]
\[ p_i^2 + n_i^2 = k^2 \]
\[ k_i^2 + n_i^2 = \varepsilon_n k^2 \]
\[-k_i \tan(k_i d) = jp_i \varepsilon_n \]
\[ n_i J_m'(bn_i) = -q_i H_m'(bq_i) \]
\[ J_m(bn_i) = H_m(bq_i) \]

(4)

In details eigenfunctions (2) and boundary conditions (3) are discussed in [3,4,5,6].

The wave potential and electromagnetic fields on the surface of the dielectric antenna are then presented in the form of a series in terms of eigenfunctions \( u_q \).

\[ U = \sum_q B_q u_q \]

Coefficients \( B_q \) of the series are found from the differential equations [2,3,4]

\[ \frac{dB_q}{dt} + j(\omega - \omega_q)B_q = \frac{(\omega - \omega_q)}{\varepsilon - \varepsilon_q} \frac{1}{k^2} \int f u_q dV \]

(5)

where integration is made over dielectric volume only, \( f \) is the source function, \( \omega_q \) is the angular frequency (complex), which satisfies the equation \( \varepsilon_q (\omega) - \varepsilon = 0 \).

Then the fields in the wave zone are found using Kirhoff integral over the surface of the dielectric (this method is used to find the antenna pattern in vertical plane. Antenna pattern in horizontal plane was found as a sum of the series in terms of eigenfunctions. For simplicity we consider the distribution of the excitation functions as a given distribution, so the input impedance is found in a standard way through total field and source current density.

3 RESULTS AND DISCUSSION

The dynamic behavior of a short cylindrical dielectrically loaded antenna was analyzed numerically using the generalized eigenfunction method described above and in [1,2,3,4].

The following parameters were chosen.

Dielectrical vertical cylinder has the radius \( b=15 cm \), height \( d=6 cm \), it placed on a horizontal conductive plane \( z=0 \).

Dielectric permittivity \( \varepsilon = 9 \)

A metal rod inserted along the vertical axis of the cylinder has the lower end at \( z=dn \) and the upper end at \( z=dk \). Two cases were investigated:

1) \( dn=0; dk=d \); 2) \( dn=0; dk=d/3 \);

The frequency of excitation 10 GHz \( (k=\omega/c=200\pi/3) \);

Distribution of current along the rod is considered as a given function (uniform or sinusoidal);

A horizontal shift of the rod \( ds \) is introduced to analyze its role in the transient period.

For the antenna pattern in a vertical plane the distribution of the fields on the cylinder surfaces as a function of time after a step excitation was calculated in the form of a series in terms of eigenfunction and then the pattern was estimated using Kirchoff’s principle for radiative apertures. For the dynamic antenna pattern in the horizontal plane the fields outside dielectric were presented in terms of eigenfunctions .(we suppose that the source is inside the dielectric).

Input impedance is presented as a function of time using the field distributions and the given current distribution.

The results are shown in the figures. It can be seen that without the horizontal shift (symmetrical excitation) horizontal antenna pattern is always symmetrical. Nevertheless, input impedance shows oscillations up to the time about 20ns (10-15 passes of the reflected radiation through the dielectric). This time should be considered as a transient period, when the operation is not a steady-state one.

A horizontal shift of the rod causes heavy deformations of the antenna pattern in the transient period. After the end of this period the pattern comes close to the symmetrical one.

A vertical displacement of the rod or changes in its length are not so dangerous for the operation of the antenna with the given configuration \( (d < b) \). One can see the changes in the steady – state antenna pattern caused by the changes in the rod position,
but dynamic changes of the pattern in the vertical plane are not as dramatic as in the horizontal plane.

4 CONCLUSION

The result show the importance of the dynamic analysis both for antenna pattern and for the input impedance. An antenna working with a very high rate of information can be in the unstable operation for the time compared with the transmitted pulse duration. It can affect negatively the whole transmitting system. According to the reciprocity principle all the receiving antennas meet the same problems.

The method presented in the paper is simple and universal. The generalized eigenfunction method can be applied to the dynamic analysis of any antenna, resonator, aperture, laser cavity or other radiating system. It helps to see clearly the configuration of the radiated field in space as a function of time. Using reasonably short calculations you can define the maximum possible rate of information which can be transmitted by your system through radiation without distortion. It becomes especially important if the information rate is so high that the frequency of radiation reaches the level where the dimensions of the radiator are more than the wavelength. For communication at 10 Mbit/s and higher instabilities in radiation pattern can be critical for the system operation, which makes the application of the dynamic analysis very important.

5 REFERENCES


Figure Captions

1. Antenna patterns for the case of the horizontal shift ds=0.75cm.
   dn=0; dk=6cm;
   1a) t=1ns vertical plane; 1b) t=1ns horizontal plane;
   1c) t=10ns vertical plane; 1d) t=10ns horizontal plane;
   1e) t=50ns vertical plane; 1f) t=50ns horizontal plane;
2. Antenna patterns for the case of the short vertically shifted rod
   ds=0.0075cm.
   dn=0; dk=2cm;
   2a) t=1ns vertical plane;
   2b) t=10ns vertical plane;
   2c) t=50ns vertical plane;
3. Input impedance for a symmetrical case ds=0.0075 cm.
   dn=0; dk=6cm;