Radiation Pattern Prediction of the Unidirectional Dielectric Radiator (UDR)

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Abstract—**This letter presents a theoretical prediction of the radiation patterns of the unidirectional dielectric radiator (UDR) using a cavity approximation. The antenna structure is first modeled as an NRD resonator, and the electromagnetic fields at the radiating aperture of the antenna structure are then determined and used to calculate the radiation fields and the radiation patterns of the antenna. The validity of the analysis is confirmed by the measurement results.**

I. Introduction

THERE HAS been increasing interest in the development of various antennas at millimeter wave frequencies for mobile and satellite communications, traffic-control and anti-collision radars, and space power combining circuits. Although the planar antenna is a strong candidate for these applications, the significant metallic ohmic loss in this type of antennas is difficult to overcome. Dielectric antennas have the merit of low loss, high efficiency, low cost, and ease of fabrication, and they are therefore suitable for millimeter-wave applications. One promising type of the dielectric antenna is one that uses the nonradiative dielectric waveguide (NRD) [1] structures, with which leaky-wave and end-fire dielectric antennas have been successfully analyzed and developed [2], [3].

A new antenna called "Unidirectional Dielectric Radiator (UDR)," uses a NRD resonator, has been proposed in [4]. Preliminary experimental investigation has shown the great potential of this antenna for many applications, such as in arrays and space power combining circuits. This type of resonant antennas has wide beamwidth and unidirectional property and retains all the advantages of NRD components. So far, there is no theoretical analysis available for this antenna. In this letter, we present for the first time an attempt to analyze this antenna and predict the radiation patterns using a cavity approximation. The antenna structure is first modeled as an NRD resonator. The resonant frequency is determined with a novel numerical hybrid technique [5]. The electromagnetic fields at the radiating aperture of the antenna structure are then calculated. The equivalent electric and magnetic current sources are then determined and used to calculate the radiation field as well as radiation patterns.

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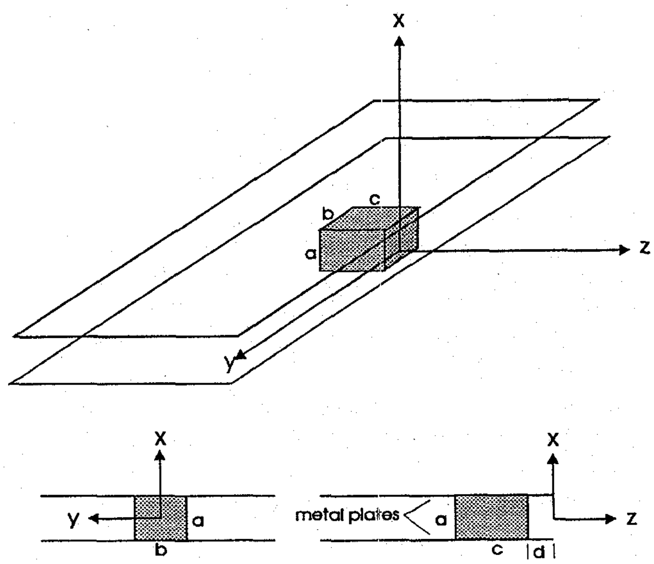

Fig. 1. Unidirectional dielectric radiator (UDR) structure.

II. Analysis

The UDR antenna [4] is shown in Fig. 1. A dielectric resonator is located in close proximity to one of the metal plate edge apertures (distance $= d$). The energy is only radiated to the open space from this aperture, while it is suppressed in others due to the cutoff properties of the NRD structure. It is well known that the radiation fields of the antenna can be determined if the electromagnetic field distributions at the aperture is known. For simplicity of the analysis, the metal plate of the antenna structure is assumed to be extended to $+\infty$, thereby resulting a typical NRD resonator. The numerical technique proposed in [5] was employed for the analysis of the resonant structure. This technique is based on a combination of the method of lines with the mode-matching method. The analysis is briefly outlined in the following.

The methods of lines with an equidistant discretization considering the symmetric planes and the absorbing boundary condition are used. With the procedure developed in [5], an implicit tangential electric-magnetic field relationship in the transformed space-spectral domain is obtained at the dielectric-air interface. Then, the coupled field components at both sides are matched through a standard mode-matching procedure with a coupling matrix. The unknown resonant frequency and the field coefficient matrix are calculated by the determinant equation. Therefore, the electromagnetic field components in the UDR radiating aperture are readily obtained

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from the tangential fields of the dielectric-air interface with the following equations:

$$\begin{aligned} e_{x(z=0)} &= \frac{\alpha}{j\omega\epsilon_0} D_x T^e \cdot \mathrm{diag}(e^{-\gamma_e d}) \cdot \vec{\phi^e}_{(z=-d^+)} \\ &\quad + T^h \gamma_h \cdot \mathrm{diag}(e^{-\gamma_h d}) \cdot \vec{\phi^h}_{(z=-d^+)} \\ e_{y(z=0)} &= \frac{1}{j\omega\epsilon_0} T^e(\alpha^2 - \gamma_e^2) \cdot \mathrm{diag}(e^{-\gamma_e d}) \cdot \vec{\phi^e}_{(z=-d^+)} \\ h_{x(z=0)} &= -\frac{\alpha}{\omega\mu_0} D'_x T^h \cdot \mathrm{diag}(e^{-\gamma_h d}) \cdot \vec{\phi^h}_{(z=-d^+)} \\ &\quad + T^e \gamma_e \cdot \mathrm{diag}(e^{-\gamma_e d}) \cdot \vec{\phi^e}_{(z=-d^+)} \\ h_{y(z=0)} &= \frac{1}{\omega\mu_0} T^h(\alpha^2 - \gamma_h^2) \cdot \mathrm{diag}(e^{-\gamma_h d}) \cdot \vec{\phi^h}_{(z=-d^+)} \end{aligned} \tag{1}$$

where $\vec{\phi^e}_{(z=-d^+)}$ and $\vec{\phi^h}_{(z=-d^+)}$ are the scalar potentials at the air side of the dielectric-air interface. α is the Fourier transformation factor in x direction, T^e and T^h are the transform matrices, D_x, D'_x, $e-m$, and $m-e$ are the discretization matrices, and $\gamma_{e,\,h}$ are the resulting diagonal matrices. The meanings of other parameters and matrices can be found in [5].

As such, the equivalent electric and magnetic currents on the aperture can be determined from the field components and the electric and magnetic vector potentials (**A** and **F**) of the radiation fields [6] can be calculated with

$$\begin{aligned} \mathbf{A} &= \frac{e^{j\beta r}}{4\pi r}(-Q_y\hat{\mathbf{x}} + Q_x\hat{\mathbf{y}}) \\ \mathbf{F} &= -\frac{e^{j\beta r}}{4\pi r}(-P_y\hat{\mathbf{x}} + P_x\hat{\mathbf{y}}) \end{aligned} \tag{2}$$

where

$$\begin{aligned} \mathbf{P} &= \int\int_{S_a} \mathbf{E_a} e^{j\beta\hat{\mathbf{r}}\cdot\mathbf{r}'} dS' \\ \mathbf{Q} &= \int\int_{S_a} \mathbf{H_a} e^{j\beta\hat{\mathbf{r}}\cdot\mathbf{r}'} dS' \end{aligned} \tag{3}$$

with S_a is the aperture area, $\mathbf{E_a}$ and $\mathbf{H_a}$ are the aperture field distributions. β is propagation constant of free space, $\hat{\mathbf{r}}$ is the unit vector of field point, and $\mathbf{r}'$ is the vector of source point. Thus, the far field of the antenna can be obtained as

$$\mathbf{E} = -j\omega\mu\mathbf{A} - j\omega\epsilon\eta\mathbf{F} \times \hat{\mathbf{r}} \tag{4}$$

where η is the wave impedance of free space.

III. Comparison

To show the validity of the approximate analysis, the calculated results are compared with the experimental ones published in [4]. Fig. 2 illustrates the E-plane and H-plane radiation patterns of a UDR working at 9.5 GHz with d =7.5 mm. The dimensions of the dielectric resonator (polystyrene, ϵ_r =2.58) are a_x =13.5 mm, b_y =13.0 mm and c_z =15.0 mm. It can be seen that a good agreement is obtained between the measurement and calculation for a large angle range. The diversity in the vicinity of ±90° may be partly due to the influence of the feed probe of the prototype and the imperfectness of the measurement environment, and also attributed to the approximation in the analysis. Fig. 3 shows the comparison of the calculated and measured 3-dB beamwidth for both E-plane and H-plane patterns versus the distance d. Again, one can see a fairly good agreement, especially for the E-plane patterns. The analysis predicts $-\infty$ cross-polar levels for both planes. This coincides with the measurement results (< -20 dB).

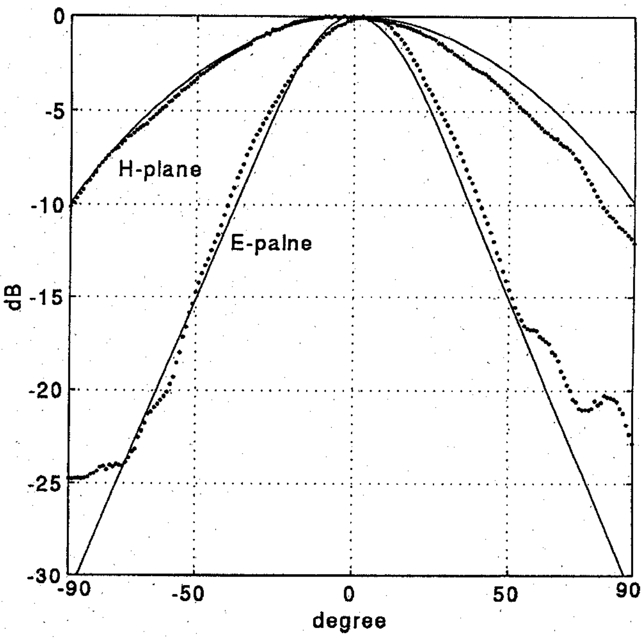

Fig. 2. E-plane and H-plane radiation patterns for d =7.5 mm. ———: calculation of this letter; ······: measurement of [4].

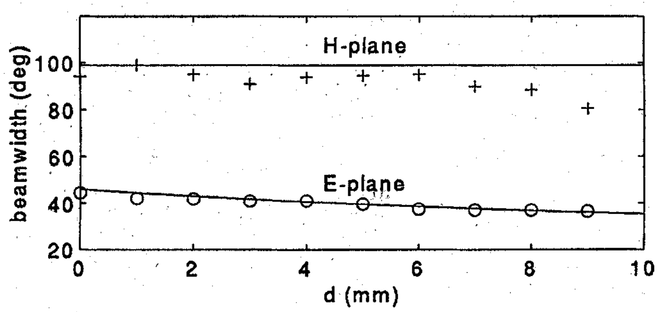

Fig. 3. 3-dB beamwidth of both E-plane and H-plane patterns versus UDR position d. ———: calculation of this letter; +, o: measurement of [4].

IV. Conclusion

In this letter, a simple yet efficient theoretical approach is presented to predict the radiation patterns of the unidirectional dielectric radiator (UDR) with a cavity approximation. A novel numerical technique is used to analyze the resonant properties and to calculate the approximate field distributions of the UDR at the aperture. Subsequently, the equivalent electric and magnetic currents are determined to calculate the radiation fields. The calculated radiation patterns of both E-plane and H-plane agree very well with the measured results. Our work is being continued to develop analytical models using the results of this letter for UDR applications in a millimetric receiver for microcellular communications.

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