Tilted Beam Characteristics of a Cylindrical Dielectric Rod Periodically Covered with Metals

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Abstract

A cylindrical dielectric rod antenna periodically covered with metals is analyzed using the body-of-revolution finite-difference time-domain method. The tilted beam can be formed by adjusting the lengths of the metal and the bare dielectric. To decrease the sidelobes caused when the beam is tilted toward the horizontal direction, a small metal reflector is attached to the top of the rod. Calculation shows that the metal reflector serves to decrease the sidelobes, while maintaining a short rod length.

1. Introduction

A dielectric rod has been used as a directive element in an antenna application at the microwave and millimetre-wave frequencies [1], [2]. The directivity is characterized by radiation fields generated at the free and feed ends of the rod [3]-[5]. It is well known that the gain of a dielectric rod antenna saturates with an increase in the rod length, and the further increase results in a periodic variation of the gain. For this reason, a high gain cannot be obtained with a uniform rod [6].

On the other hand, a dielectric rod periodically covered with metals (a so-called Dash-Hollow rod [7]) leads to an increase in the gain. We numerically demonstrate that high gain characteristics can be obtained using this configuration [8].

The purpose of this article is to reveal the fact that a tilted beam can be formed by adjusting the lengths of the metal and the bare dielectric. To evaluate the wave propagating along the rod, the body-of-revolution finite-difference time-domain (BOR-FDTD) method is employed [9]-[11]. The use of the BOR technique enables us to efficiently calculate the radiation from an antenna with circular symmetry [6], [12].

Before investigating the radiation characteristics of the dielectric rod antenna periodically covered with metals, we first discuss the optimum lengths of the metal (L_m) and the bare dielectric (L_d). These lengths must satisfy an in-phase condition in the desired direction. We first show the optimum values of L_m and L_d for the in-phase condition as a function of tilt angle. We then discuss the gain against the number of metal elements and the radiation patterns for some tilt angles.

Next, to decrease the sidelobes caused when the beam is tilted toward the horizontal (90°) direction, a small metal reflector [13] is attached to the top of the rod. It is found that the metal reflector has the effect of decreasing the sidelobes and increasing the gain, with a short rod length being maintained.

2. Configuration and Numerical Method

Fig. 1 illustrates the configuration of a cylindrical dielectric rod periodically covered with metals. The rod with a relative permittivity of ε_r = 2.54 (Polystyrene) is fed by a circular metallic waveguide. The bore of the metallic waveguide, which is the same as the diameter of the rod, is $2\rho_{rod}$ = 17.475 mm. The waveguide is excited with the TE_{11} mode at a frequency of 11 GHz ($\lambda_0 \cong$ 27.3 mm). The rod is tapered in the metallic waveguide so that the impedance matching may be made between the air-filled and dielectric-filled regions. A return loss of more than 19dB is achieved for a taper length L_{in} of greater than $2.0\lambda_0$.

The radiation mode is generated at discontinuities between the metal and the bare dielectric. Therefore, this antenna can be regarded as an array composed of short dielectric rods aligned in the z-axis direction. The lengths of the metal and the bare dielectric, which are respectively designated as L_m and L_d, are determined in such a way that the radiation from each bare dielectric adds in phase toward the direction of the desired tilt angle θ_t. This leads to the following relation:

$$2\pi\left(\frac{L_d}{\lambda_g}+\frac{L_m}{\lambda'_g}\right)-2\pi\cos\theta_t\left(\frac{L_d+L_m}{\lambda_0}\right)=2\pi \qquad (1)$$

where λ_g and λ_g' are the guided wavelengths in the bare dielectric rod and in the rod with the metal, respectively.

In the analysis, it is assumed that the cylindrical metals are perfectly conducting. The wave propagating along the rod is calculated by the BOR-FDTD method developed for the analysis of axially symmetric structures [9], [10]. By the use of the BOR technique, a circular interface is accurately described in the cylindrical co-ordinates based on Yee's mesh.

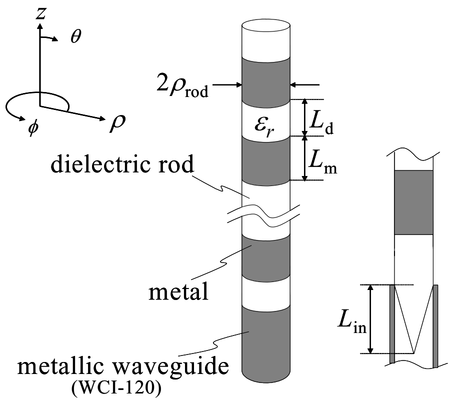


Fig. 1: Configuration

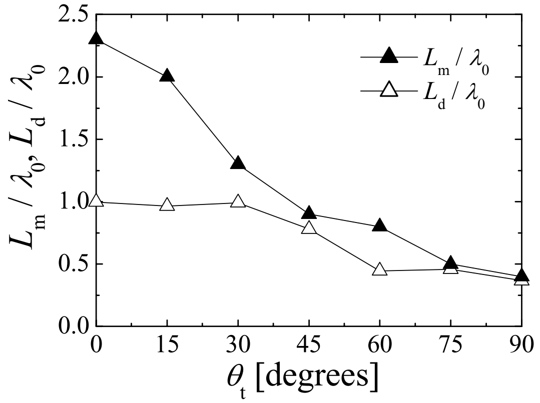


Fig. 3: Optimum metal and bare dielectric lengths (N=6)

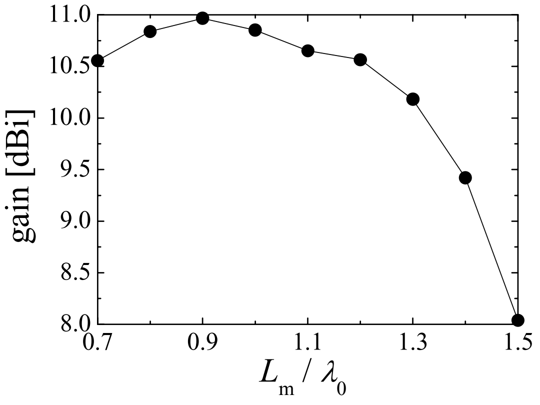


Fig. 2: Gain as a function of L_m ($\theta_t = 45^\circ$, N=6)

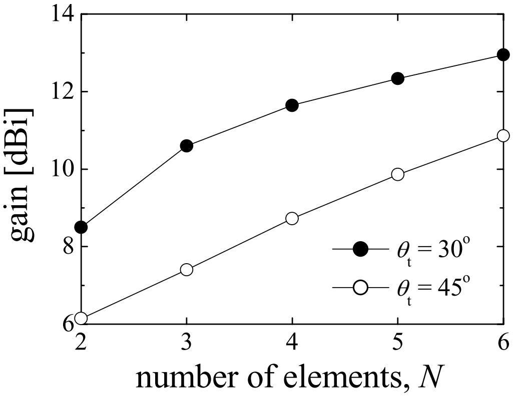


Fig. 4: Gain as a function of the number of elements

Furthermore, the partial derivative with respect to ρ can be performed analytically. Consequently, the original three-dimensional (ρ, θ, z) model is reduced to an equivalent two-dimensional (ρ, z) one. This leads to the fact that the wave propagating along a long rod can efficiently be analyzed. The grid widths are fixed to be $\Delta\rho = 2\rho_{rod}/30$ and $\Delta z = \lambda_0/100$ throughout this analysis.

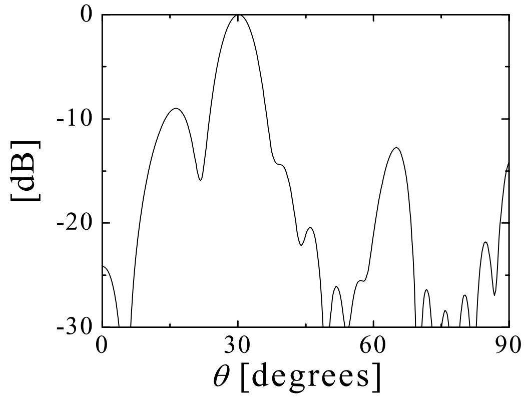
The excitation scheme of a +z-propagating incident waveform [14] is used for a continuous wave simulation of the TE_{11} mode. The directivity is calculated from the fields on a virtual closed surface regarded as a Huygens plane which encloses the antenna structure in the computational region. As an absorbing boundary condition, the second-order Higdon's operator [10] is used.

3. Basic Characteristics

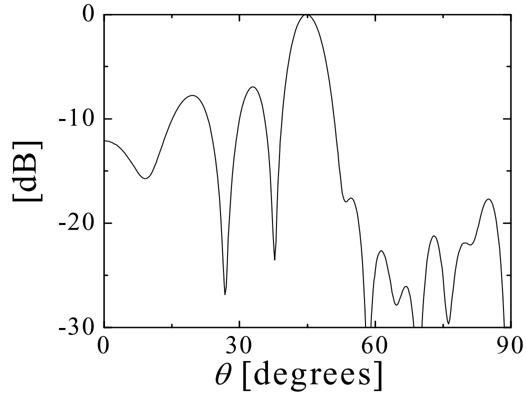
In order to obtain a high gain, we first determine the optimum lengths of L_m and L_d. Fig. 2 shows the gain characteristic for $\theta_t = 45^\circ$ and the number of metal elements N=6 as a function of L_m. Note that the value of L_d is chosen so as to satisfy Eq. (1) for each L_m. It is found that the maximum gain for $\theta_t = 45^\circ$ is obtained when L_m is taken to be $L_m = 0.9\lambda_0$. Optimum values of L_m and L_d as a function of θ_t are shown in Fig. 3. It is found that both L_m and L_d decrease with an increase in θ_t. The values of L_m and L_d approach the same value, as θ_t is increased.

As an example, the gain characteristics for $\theta_t = 30^\circ$ and 45°as a function of the number of elements N are shown in Fig. 4. The gain tends to increase as N is increased. For $N = 6$, gains of 13.0dBi and 10.9dBi are obtained for $\theta_t = 30^\circ$ and 45°, respectively. Figs. 5(a) and (b) present the corresponding radiation patterns in the E-plane. It is confirmed that the tilted beam is successfully formed by adjusting the lengths of the metal and the bare dielectric. The half-power beamwidth is calculated to be 7° for $\theta_t = 30^\circ$ and $\theta_t = 45^\circ$.

When the beam is tilted toward the horizontal ($\theta_t = 90^\circ$) direction, large sidelobes are generated toward the end-fire direction. This property is clearly observed in the radiation pattern in Fig. 6, where the pattern in the E-plane for $N = 8$ is typically presented. The large sidelobes result from the fact that the appreciable power reaches the top of the rod. The



(a) $\theta_t = 30^\circ$



(b) $\theta_t = 45^\circ$

Fig. 5: Radiation patterns (E-plane, $N = 6$)

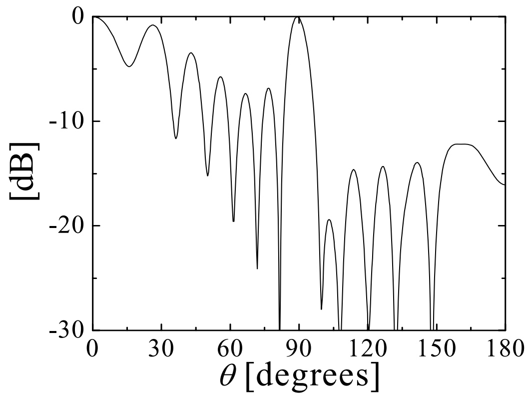


Fig. 6: Radiation pattern (E-plane, $\theta_t = 90^\circ$, $N = 8$)

remaining power is radiated from the top of the rod toward the end-fire direction, resulting in the large sidelobes. One way to solve this problem is to increase the number of elements in such a way that most of the power is radiated as

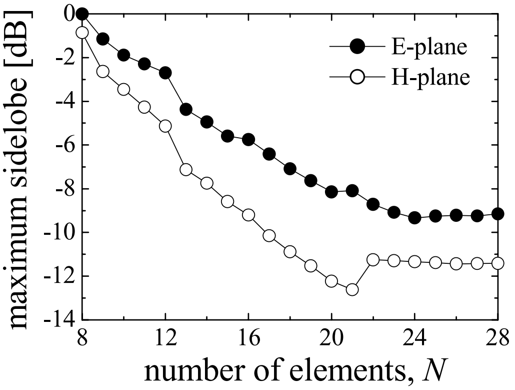


Fig. 7: Maximum sidelobe level as a function of N ($2\rho_{mr} = 0$)

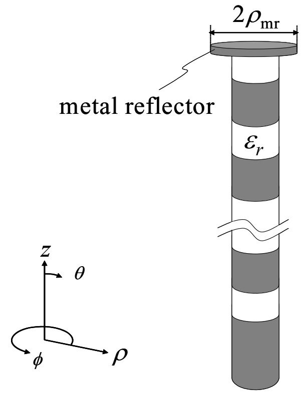


Fig. 8: Configuration

the field propagates, so that negligible power reaches the top of the rod. Fig. 7 shows the maximum sidelobe level as a function of the number of elements N. It is found that the sidelobes in both E- and H-planes reduce as N is increased. However, the resultant rod length becomes very long and the beamwidth becomes narrow as N is increased.

4. EFFECTS OF ADDING A SMALL METAL REFLECTOR

To suppress the sidelobes with the short rod being maintained, a small metal reflector is added to the top of the rod, as shown in Fig. 8. The diameter of the metal reflector is designated as $2\rho_{mr}$. The addition of the metal reflector contributes to the suppression of radiation from the top of the rod, so that the remaining power is reflected at the top of the rod, generating a backward wave toward the feed end. The backward wave is reradiated at the discontinuity between the metal and the bare dielectric. Since the backward wave provides the radiation whose direction is the same as the forward wave, the metal reflector suppresses the sidelobes, while maintaining a short rod length.

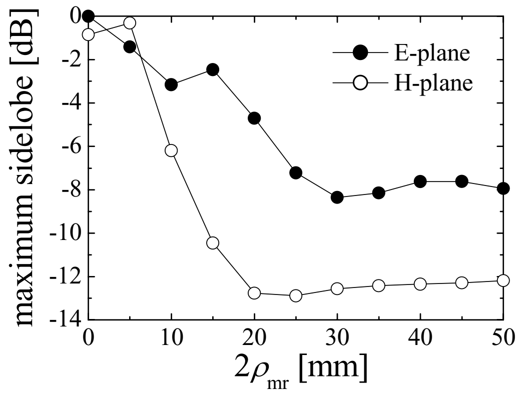
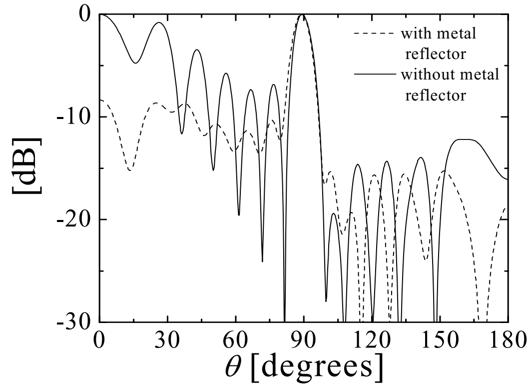
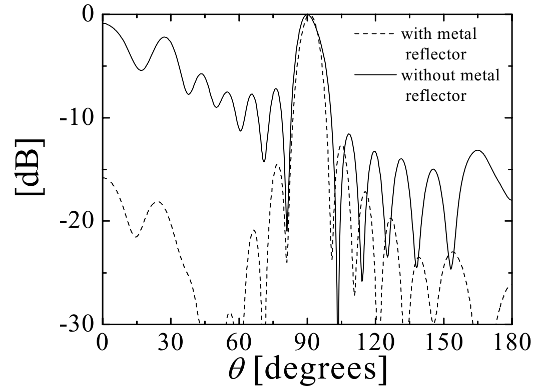


Fig. 9: Maximum sidelobe level as a function of $2\rho_{mr}$ ($\theta_t = 90^\circ$, $N = 8$)



(a) E-plane



(b) H-plane

Fig. 10: Radiation patterns ($\theta_t = 90^\circ$, $N = 8$)

Fig. 9 shows the maximum sidelobe level as a function of $2\rho_{mr}$. It is found that the maximum sidelobe level for $2\rho_{mr}$ = 30 mm decreases by more than 8dB in E-plane and more than 12dB in H-plane. We choose this diameter in the following analysis.

Figs. 10(a) and (b) show the radiation patterns for N=8 in the E- and H-planes, respectively. The broken and the solid lines present the results for the antennas with and without the metal reflector, respectively. The maximum sidelobe level is reduced from 0dB to -8.3dB in the E-plane and from -0.9dB to -12.6dB in the H-plane. That is to say, the sidelobes can be decreased due to the addition of the metal reflector even when N is decreased from 20 to 8. The half-power beamwidths of the antennas with and without the metal reflector are calculated to be 8°. A gain of 9.7dBi is obtained, which is higher than that without the metal reflector by 2.8dBi.

5. Conclusions

Cylindrical dielectric rod antennas periodically covered with metals have been analyzed using the BOR-FDTD method. It is revealed that the tilted beam can be formed by adjusting the length of the metal. Optimum lengths of the metal and the bare dielectric are provided to obtain the radiation beam toward the direction of the desired tilt angle. To decrease the sidelobes caused when the beam is tilted toward the horizontal direction, a small metal reflector is attached to the top of the rod. It is found that the sidelobes are reduced from 0dB to -8.3dB in the E-plane and from -0.9dB to -12.6dB in the H-plane, while maintaining a short rod length. Furthermore, it is shown that a gain of 9.7dBi is obtained, which is higher than that without the metal reflector by 2.8dBi.

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