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High-Gain Characteristics of a Dielectric Tube Antenna

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1. Introduction

An endfire antenna is known as a simple high gain antenna in the microwave and millimeter-wave regions [1]-[4]. The attainable gain is often estimated by the Hansen-Woodyard condition [1]. Although the estimation by the Hansen-Woodyard condition is relatively good in the conventional endfire antennas, this often discourages us to realize a higher gain antenna with an acceptable axial length. Note that the radiation mechanism of the endfire antenna is explained by the so-called discontinuity radiation concept, in which the antenna is regarded as an array of two aperture sources situated at the feed and open ends [3]. We should also recall that the Hansen-Woodyard condition corresponds to an ideal situation that the two aperture sources are identical (an excitation efficiency of 50%). This means that the ideal situation leads to a gain increase by approximately 3dB from the original gain evaluated from a single aperture source. In other words, the total gain should be limited by the original gain from each aperture source. Therefore, a high gain may be obtained, provided that the aperture field with a planar phase distribution is sufficiently extended in space and that the two aperture fields are generated almost evenly.

In this article, we investigate high gain properties of a dielectric tube antenna fed by a metallic waveguide [5]. Since the effective index of the dielectric tube is close to unity, it serves to extend the surface wave in space. To efficiently excite the dielectric tube, we introduce a small dielectric sphere [6] between the tube and the metallic waveguide. We numerically demonstrate that the proposed antenna achieves a gain higher than that estimated by the Hansen-Woodyard condition.

2. Dielectric Tube Antenna Fed by a Metallic Waveguide

We first study the basic characteristics of a dielectric tube whose relative permittivity is ε_r=2.1. The tube is fed by a metallic waveguide (WCI-120) whose inner diameter is designated as 2ρ, as shown in Fig. 1. The outer and inner diameters of the tube are, respectively, taken to be $2\rho_{out} \approx 0.8\lambda_{12}$ and $2\rho_{in} \approx 0.6\lambda_{12}$, where the center operating wavelength is chosen to be $\lambda_{12} = 25$ mm (f = 12 GHz). The power of the TE_{11} mode excited in the metallic waveguide is partially transferred to the HE_{11} mode (surface wave) of the dielectric tube. In other words, part of the excited power is radiated at the feed end and transferred to the space wave, while the surface wave is radiated from the open end. The surface wave interferes with the space wave, so that the gain should be a function of axial length L_{ax}.

To efficiently excite the dielectric tube, we have to pay attention to the impedance matching between the waveguide and the tube. Since the effective index (β/k) of the tube is roughly close to unity, we may focus our attention to the matching between the waveguide and the air region. Fortunately, the characteristic impedance of the metallic waveguide can be small due to the insertion of dielectric. Therefore, we propose the configuration shown in Fig. 1(b). The dielectric, which is the same as the tube, is tapered into the metallic waveguide to reduce the impedance in the waveguide. Our preliminary calculation shows that the characteristics impedance of the waveguide is 220Ω, while that for the waveguide filled with the dielectric is 147Ω, which is close to the intrinsic impedance of the air region.

In the analysis, we employ the body-of-revolution finite-difference time-domain (BOR-FDTD) method [7], in which a circular interface is accurately described in the cylindrical co-ordinates based on Yee's mesh. The partial derivative with respect to ϕ can be performed analytically, so that the original three-dimensional (r, ϕ, z) model is reduced to an equivalent two-dimensional (r, z) one. This greatly contributes to reduction in the computational time and memory. The calculation parameters are chosen to be $\Delta r = \rho/30 \approx 0.29$ mm and $\Delta z = 0.25$ mm. The boundary condition based on the second-order Higdon's operator is placed for absorbing outgoing waves at the computational edges.

Fig. 2 shows the gain characteristic as a function of axial length L_{ax}. For reference, the data obtained with the conventional rod ($\rho_{in} = 0$) are also presented. It is seen that the gain of the conventional rod oscillates as a function of axial length (The maximum gain is evaluated to be 13.5dBi at $L_{ax} = 2\lambda_{12}$). In contrast, the gain of the tube gradually increases up to approximately 18dBi due to the reduction in the effective index. Further increase of the axial length results in the degradation of the gain. The radiation pattern for $L_{ax} = 12\lambda_{12}$ is shown in Fig. 3. For comparison, the pattern for the conventional rod for $L_{ax} = 2\lambda_{12}$ is also shown. As expected, the pattern of the tube is sharper than that of the conventional rod. The half-power beamwidth (HPBW) and the first side-lobe level are, respectively, calculated to be ±7 degrees and 6.8dB in the E-plane. Similar pattern is also observed in the H-plane.

3. Tube Antenna Fed by a Waveguide-Excited Dielectric Sphere

To obtain a high gain, we have to extend the field distribution of the surface wave mode in space, while maintaining a reasonable excitation efficiency of the tube. To do this, we introduce a small dielectric sphere with a radius of $\rho_{out} = \lambda_{12}$ at the junction between the metallic waveguide and the dielectric tube. Before studying a combined configuration, we first consider the radiation property of the small dielectric sphere shown in Fig. 4. Fig. 5 shows the calculated gain of the dielectric sphere as a function of frequency. Note that the introduction of a straight part whose length is designated as L_{st} leads to a high gain property. Therefore, we adopt the modified configuration and propose the combined configuration illustrated in Fig. 6, where half the configuration is illustrated due to the circular symmetry. The thickness of the tube is adjusted so as to realize the almost the same propagation constant as that in Fig. 1, so that an optimized axial length ($L_{ax} \approx 12\lambda_{12}$), where the highest gain is observed, is almost the same. A typical radiation pattern at 12 GHz is shown in Fig. 7, together with the pattern with the original tube shown in Fig. 1. It is clear that the pattern of the proposed antenna is sharper with a reduced sidelobe level of less than -10dB. The HPBWs are calculated to be ±7 degrees and ±6.5 degrees in the E-plane and H-plane, respectively.

The frequency response of the proposed antenna is shown in Fig. 8. It is found that the gain shows a wideband characteristic. A gain of more than 21dBi is obtained over a frequency range of 10.4 to 12.6 GHz. A maximum gain of 21.7dBi is obtained at 12 GHz. The return loss is more than 15dB over a frequency range of 10.5 to 13 GHz. It is interesting to compare the gain of the proposed antenna with that obtained with the design guideline presented by Zucker [1], in which the gain is estimated by $G = mL_{ax}/\lambda$, where the case for $m = 7$ corresponds to the Hansen-Woodyard gain, and that for $m = 10$ to the maximum gain. Calculation shows that for $L_{ax} = 12\lambda$, these gains are calculated to be 19.2dBi and 20.8dBi, respectively. It is worth mentioning that the gain of the proposed antenna is higher than those estimated gains.

4. Conclusions

The BOR-FDTD method has been employed to investigate the radiation characteristics of a dielectric tube antenna fed by a metallic waveguide. To enhance the excitation efficiency of the tube, we adopt a small dielectric sphere at the junction between the metallic waveguide and the dielectric tube. It is found that the proposed antenna of an axial length of $L_{ax} = 12\lambda_{12}$ exhibits a gain of more than 21dBi over a wide frequency range of 10.4 to 12.6 GHz. It is revealed that the obtained gain is higher than that estimated by the Hansen-Woodyard condition.

References

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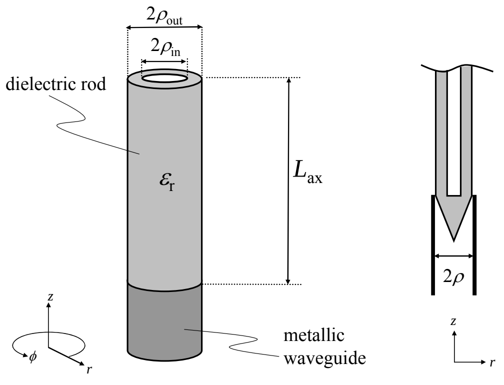

(a) (b)

Fig. 1: Dielectric tube antenna

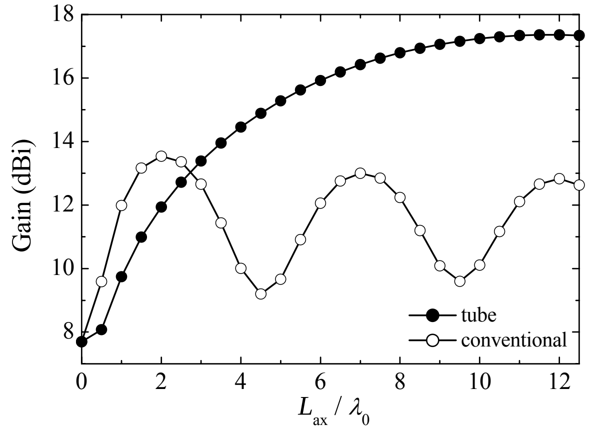

Fig. 2: Gain characteristic as a function of L_{ax}

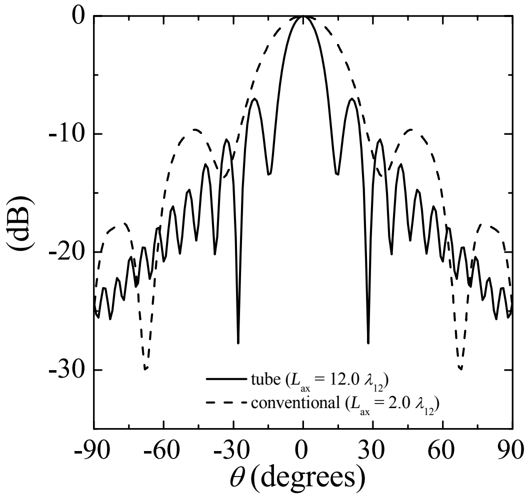

Fig. 3: Radiation pattern (E-plane)

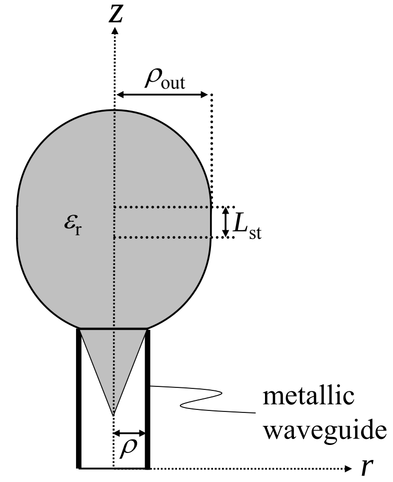

Fig. 4: Dielectric sphere

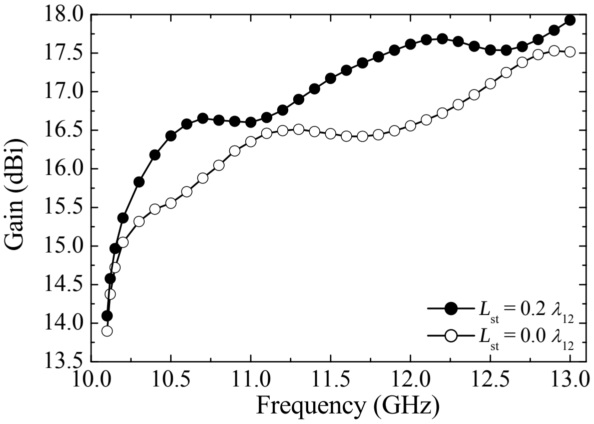

Fig. 5: Frequency response of gain

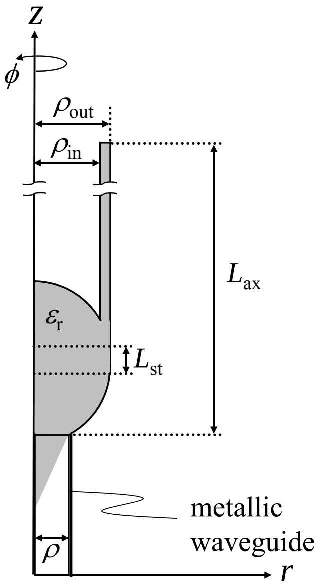

Fig. 6: Modified tube antenna fed by a waveguide-excited dielectric sphere

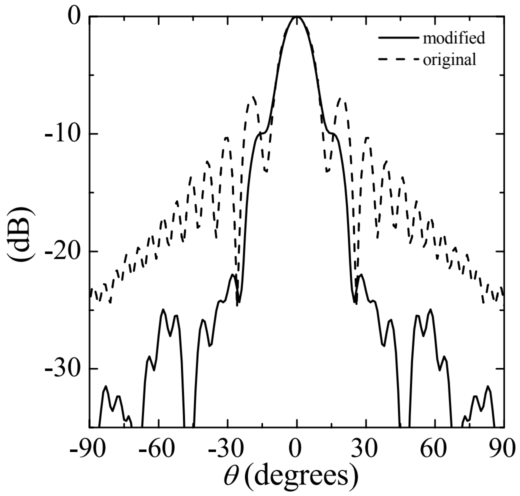

Fig. 7: Radiation pattern (E-plane)

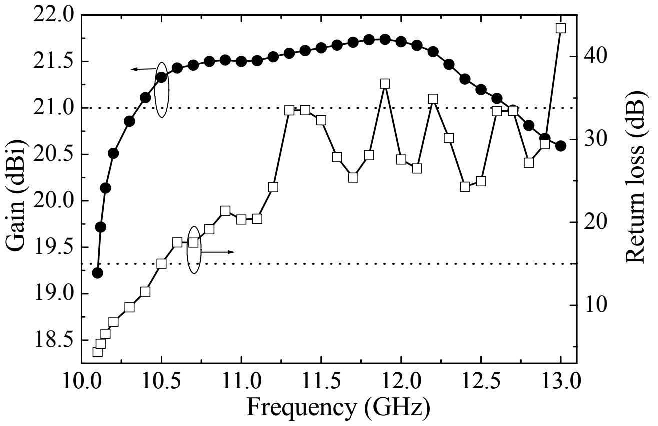

Fig. 8: Frequency responses of gain and return loss