Design of Millimeter-wave Dielectric Antenna Array Integrated with Dielectric Waveguide Using Topology Optimization

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Dielectric waveguides have been attracting attention as a transmission line that allows for highly flexible circuit configuration in the millimeter-wave band. The objective of this study is to develop a dielectric antenna array integrated with a dielectric waveguide. By configuring the radiating element of the antenna from a dielectric material, it is expected that the loss between the dielectric waveguide and the antenna can be suppressed. In this study, the analysis model of the antenna array integrated with the dielectric waveguide consists of a T-shaped branch and two radiation elements, and beam tilting is performed by the structural design of the branch. Topology optimization using the normalized Gaussian function network (NGnet), which has a high degree of design freedom, is introduced into the structural design of the branch. The structural design is performed by setting the desired tilt angle in 76 GHz band. Although the radiation loss is still large, the optimization results show that beam tilting is possible even with low relative permittivity of $\varepsilon_r = 2.6$.

***Index Terms*— dielectric waveguides, dielectric antennas, millimeter wave, topology optimization.**

I. Introduction

Waveguides are often used as low-loss transmission lines connecting antennas and devices in the millimeter-wave band. A waveguide made of a hollow metal tube has low loss even at high frequencies and can be used in frequency bands over 100 GHz. However, it is difficult to configure complex circuits compactly using waveguides. Therefore, dielectric waveguides have attracted attention as transmission lines that allow for flexible circuit configuration [1][2]. Dielectric waveguides can be easily realized with complex branching sections. On the other hand, the reflection loss at the connection with the metal antenna is a problem [2]. In order to suppress the effect of this reflection, it is effective to integrate the antenna and the dielectric waveguide into one structure. Antennas using a dielectric rod are called a dielectric resonator antenna (DRA) [3]. By using a dielectric rod as a radiation element, it is expected that the reflection loss due to the difference in the medium between the dielectric waveguide and the antenna can be suppressed. In addition, the dielectric rod can have a function like a dielectric lens [4].

The purpose of this study is to develop a dielectric antenna array integrated with a dielectric waveguide. First, the transmission characteristics of dielectric waveguides are analytically clarified for fundamental investigation. The FDTD method (finite difference time domain method) is used for analysis. Next, it is clarified whether the beam can be tilted in any direction by designing the dielectric branch structure. The design model consists of a T-shaped branch and two radiation elements. Topology optimization, which has a high degree of design freedom, is introduced into the structural design of the branch [5].

In this study, the optimal design is performed for an analysis frequency of 76 GHz in the milli-meter wave band. Therefore, a dielectric waveguide of WR-10 standard (2.56 × 1.28 mm) is adopted and modeled using FDTD method with the cell size of 0.08 mm.

II. Analysis of Straight Dielectric Waveguide

To confirm the transmission characteristics of the dielectric waveguide, the straight type of dielectric waveguide is modeled. The length of the dielectric waveguide is set to 8.0 mm. A waveguide converter is also modeled and placed in the input side of dielectric waveguide. The continuous wave in TE_{10} mode is provided from the waveguide converter. The input power at the power supply side and the output power at the termination side are calculated to obtain the loss factor which is defined in Fig.1. Figure 1 shows the result of calculating the loss factor by changing the relative permittivity of the dielectric waveguide. Note that the loss tangent tanδ = 0.003 is given. Figure 1 shows that although radiation loss is observed, transmission is possible using only the dielectric waveguide. The loss factor decreases as the permittivity increases, and the transmission characteristics tend to improve.

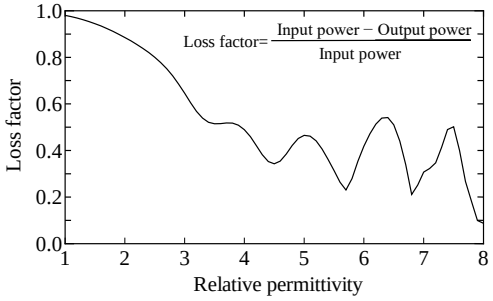


Fig. 1. Loss factor vs relative permittivity.

III. Design Model of Topology Optimization

The dielectric antenna array integrated with the dielectric waveguide is modeled as shown in Fig. 2. The structural design using topology optimization is performed for the design domain enclosed in the red frame in Fig. 2. Through optimization, the beam tilt is realized by controlling the phase of the two radiation elements. In this study, the normalized Gaussian function network (NGnet) is introduced as topology optimization

method [6][7]. Using NGnet, it is possible to design with a high degree of freedom, such as drilling holes, and it is expected to obtain a smooth structure that can be prototyped using a 3D printer. The weight coefficients of each Gaussian base of NGnet are optimized using μGA (micro genetic algorithm) [8].

In the design region in Fig.2, the number of NGnet bases consists of 14 in the z direction and 4 in the x direction. The thickness direction (y direction) is designed as a uniform structure. The electric field value E_θ at the desired tilt angle θ is calculated to obtain the objective function. In practice, the objective function OF is set as in (1).

$$OF = E_\theta - E_{avg} \quad (1)$$

Where E_{avg} is the average electric field value at angles other than θ. E_θ and E_{avg} are calculated in the far field.

IV. Optimization Results

When the permittivity of the dielectric is set to ε_r=2.6 assuming PLA (polylactic acid) which is a filament material for 3D printers, the optimization results for the desired tilt angles of 45, 0, and 315 degrees are shown. Figure 3 shows the shift in the objective function, Figure 4 shows the radiation patterns, and Figure 5 shows the shape of the design region, respectively. The actual model is in 3D. By optimizing the branch, the directivity changes compared to when the entire design region is filled with dielectric. These results indicate that beam tilting to an arbitrary angle is possible by changing the shape of the dielectric. The dielectric materials tended to gather more in the direction of the designed tilt angle in Fig.5.

In the future, we plan to study structures that have low radiation loss and are easy to fabricate. The NRD guide (Non-Radiative Dielectric waveguide) is one promising structure.

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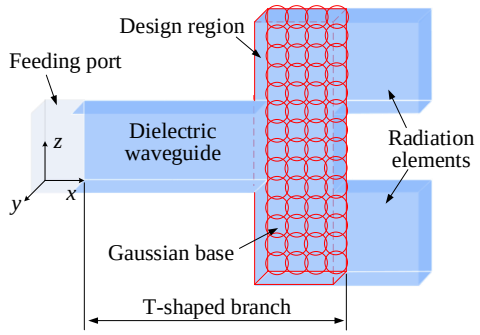


Fig. 2. Analysis model and design region.

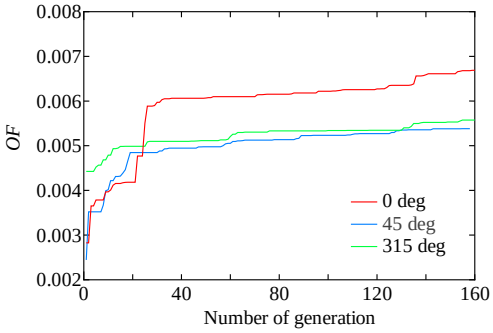


Fig. 3. Shift in objective function.

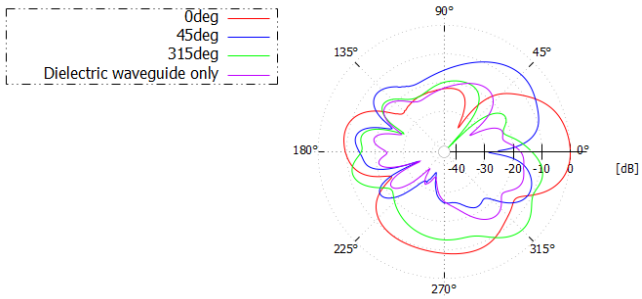
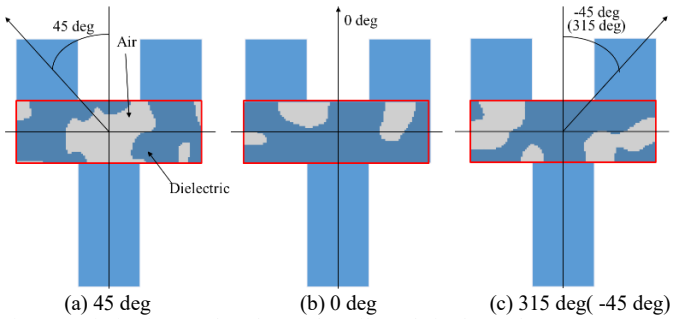


Fig. 4. Optimization results (radiation pattern when tilt angle is changed).



(a) 45 deg (b) 0 deg (c) 315 deg(-45 deg)

Fig. 5. Optimization results (shape when tilt angle is changed).