Design of Small Dielectric Lens for Slot Antenna Using Topology Optimization

Keiichi Itoh[1] and Hajime Igarashi[2], *Member, IEEE*

[1] Akita National College of Technology, Akita, Akita 011-8511, Japan, itok@ipc.akita-nct.ac.jp
[2] Graduate School of Information Science and Technology, Hokkaido University, Sapporo, Hokkaido 060-0808, Japan

This paper reports a novel 3D topology optimization method for a dielectric lens antenna. The proposed method designs the shape of the dielectric lens, which is small as compared with the wavelength and is loaded on the aperture of the waveguide slot antenna. In this topology optimization, the On/Off method using the normalized Gaussian networks (NGnet) is adopted to obtain smooth lens shape. As an example of the optimization using this method, the minimization of the beamwidth of the main beam is performed. When the number of the Gaussian basis of the NGnet is 3×3×3 or more, the main beam of the antenna loading the optimized lens becomes narrow. Also, the lens shape becomes not the checkerboard patterns but smooth distribution by using the NGnet.

***Index Terms*— FDTD method, genetic algorithm, normalized Gaussian networks, topology optimization**

I. Introduction

SINCE a dielectric lens antenna realizes high aperture efficiency, it is often used as a highly efficient directional antenna [1]. As the lens shape to converge the main beam of small lens antennas, the extended hemispherical type [1] and the spherical type [2] have been proposed. If it is possible to realize desired radiation patterns only by loading the dielectric lens, it is expected that not only a directional antenna with a narrow beamwidth but also a wide angle fan beam antenna can be realized. But, to design the antenna with the desired beam form by loading the dielectric lens, a new design method that can change the shape of the lens freely is required.

In this paper, a novel antenna design method using 3D topology optimization of the dielectric lens shape is proposed. Of several topology optimization methods, the On/Off method for the voxel mesh is adopted [3]. The lens shape is expressed by two states which are the dielectric and the air. The larger the number of the voxel, the more the combination of the dielectric and the air becomes enormous. As the results, the optimized shape tends to be the checker board patterns.

To obtain the lens shape with smooth boundary, we apply the normalized Gaussian networks (NGnet) to 3D topology optimization method. To confirm the design capability of the proposed method, this paper reports design example of the shape of the small dielectric lens to narrow the beamwidth of the main beam which is radiated from the antenna. The shape of the dielectric design region is the cube with 20 mm each side. Since the analysis frequency is set to 12 GHz, the lens size is smaller than 25 mm of wavelength.

II. Topology Optimization Method

A. On/Off method based on NGnet

The outline of the On/Off method based on NGnet is shown in Fig. 1 [4]. As an example, the case which three Gaussian functions $G(\boldsymbol{x})$ are linearly arranged on the $\boldsymbol{x}$ axis as shown in Fig. 1(a) is described. First, as shown in Fig. 1(b), the normalized Gaussian function $b(\boldsymbol{x})$ is calculated for the input $\boldsymbol{x}$. The range of $b(\boldsymbol{x})$ becomes [0, 1], because it is normalized by the sum of the Gaussian functions for each input $\boldsymbol{x}$. Next, each $b(\boldsymbol{x})$ is multiplied by the weighting coefficient w, and the sum of $w \times b(\boldsymbol{x})$ is calculated for each input $\boldsymbol{x}$. The range of w is set to [-1,1]. Finally, the output $y(\boldsymbol{x})$ changes smoothly with respect to the input $\boldsymbol{x}$ as shown in Fig. 1(c).

By using the obtained output $y(\boldsymbol{x})$, On/Off states are set as follows: $\boldsymbol{x}$ is on when $y(\boldsymbol{x}) \geq 0$, and $\boldsymbol{x}$ is off when $y(\boldsymbol{x}) < 0$. The Gaussian function $G_k(\boldsymbol{x})$, the normalized Gaussian function $b_i(\boldsymbol{x})$, and the output $y(\boldsymbol{x})$ are defined as follows.

$$G_k(\boldsymbol{x}) = \frac{1}{(2\pi)^{D/2}|\Sigma_k|^{1/2}} \times \exp\left[-\frac{1}{2}(\boldsymbol{x}-\boldsymbol{\mu}_k)^T \Sigma_k^{-1}(\boldsymbol{x}-\boldsymbol{\mu}_k)\right] \quad (1)$$

$$b_i(\boldsymbol{x}) = \frac{G_i(\boldsymbol{x})}{\sum_{k=1}^{N} G_k(\boldsymbol{x})} \quad (2)$$

$$y(\boldsymbol{x}) = \sum_{i=1}^{N} w_i b_i(\boldsymbol{x}) \quad (3)$$

where w_i is the weighting coefficient, N is the number of the Gaussian functions, D is the dimension of the input $\boldsymbol{x}$, $\boldsymbol{\mu}_k$ and Σ_k are the center vector and the covariance matrix of the Gaussian function k. These are the optimization parameters.

B. Topology optimization using NGnet

On/Off states are defined as the dielectric and the air respectively, and the shape of the dielectric lens is optimized according to the above procedure. In this study, only the weighting coefficient is optimized among three parameters. To optimize the weighting coefficient, the evolutional calculation method, which is called the micro genetic algorithm (μGA), is adopted [2][5]. The weighting coefficient is treated as the gene in the μGA. To obtain smoother lens shape, the gene is given as not the bit-coded type but the real-coded type.

The objective function OF of the μGA is evaluated by the FDTD calculation. The number of the individuals is five. As the generation progresses, it is presumed that the absolute value of the weight coefficient exceeds 1 by the crossover. Therefore, the weighting coefficient is normalized in each generation so that its range is always modified to [-1, 1].

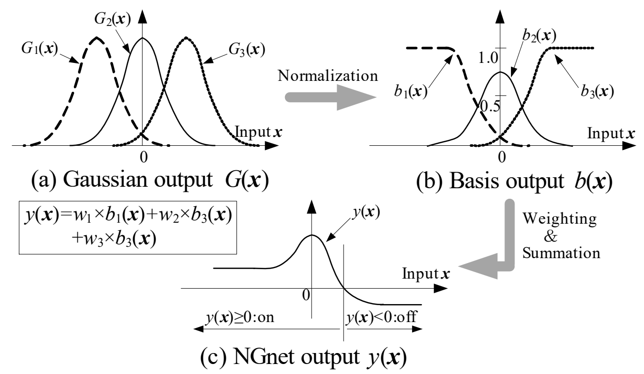

Fig. 1. Outline of On/Off setting method using NGnet.

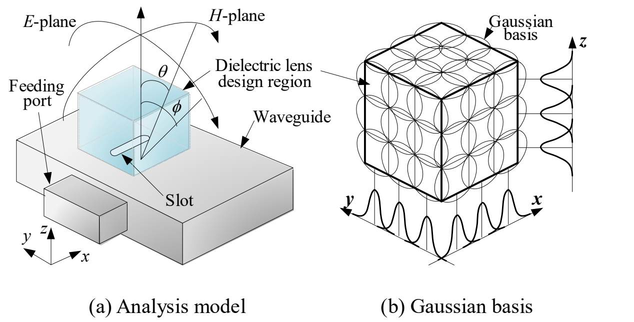

Fig. 2. Outline of analysis model and placement of Gaussian basis in dielectric lens design region.

III. 3D Topology Optimization of Dielectric Lens

A. Analysis model

Because the cell size is set to 0.5 mm, the number of the cell in the design region is 40×40×40. As shown in Fig. 2, the design region is placed on the aperture of 1-slot type waveguide slot antenna. The relative permittivity in the design region is 2.2 in case of the dielectric and 1.0 in case of the air. The Gaussian basis is arranged in 3D as shown in Fig.2 (b) which is 3×3×3 case. The excitation source of TE_{10} mode is fed in the feeding port. The slot length is set to 12.5 mm which is the resonance length.

For the purpose of improving the directivity by the dielectric lens, the shape of the dielectric lens is optimized to minimize the beam width of the main beam. Actually, by calculating -20 dB beamwidth BW_H and BW_E from the *H*-plane and *E*-plane radiation patterns, the sum of both is set as the objective function *OF*. In this case, to shorten the calculation time, the far field is calculated by transforming the near field.

B. Optimization results

The relation between the number of the Gaussian basis and the convergence speed of the *OF* is examined by changing the number of the basis. As shown in Fig. 3, it is found that, when the number of the basis is 3×3×3 or more, the solution is found to converge enough. The shapes of the optimized lenses are shown in Fig. 4. The lens shapes are confirmed to become not the checker board patterns but smooth distribution. Also, as the number of bases increases, the lens shape becomes more complicated, but the convergence speed becomes slower.

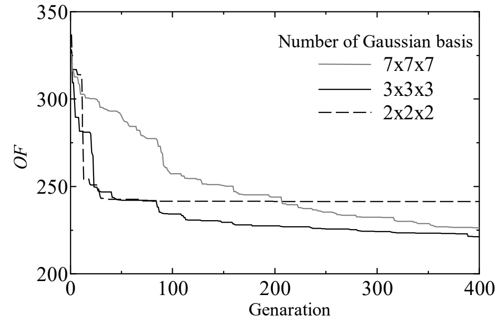

Fig. 3. Comparison of changes in *OF*.

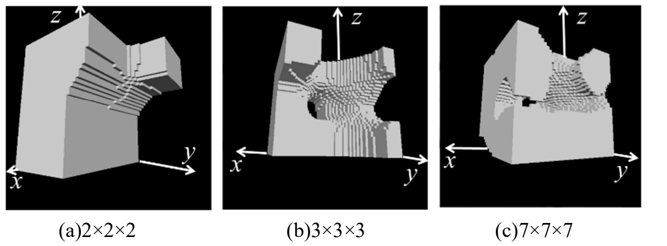

Fig. 4. Shapes of optimized lenses.

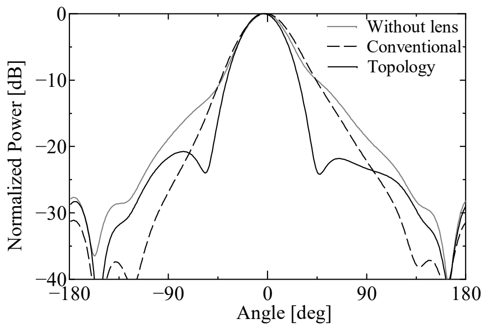

Fig. 5. Comparison of *H*-plane radiation patterns.

The radiation patterns in case of 3×3×3 bases are shown in Fig. 5. It is confirmed that the main-lobe of the antenna loaded with the topology optimized lens becomes narrower than that with the conventional extended hemispherical lens.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 15K06093 and the collaborative research program, information initiative center, Hokkaido University, Sapporo, Japan.

References

[1] G. Godi, R. Sauleau, D. Thouroude, “Performance of reduced size substrate lens antennas for millimeter-wave communications”, *IEEE Trans. Antennas Propag.*, Vol.53, No.4, pp.1278–1286, 2005.

[2] K. Itoh, K. Miyata and H. Igarashi,"Evolutional design of waveguide slot antenna with dielectric lenses", *IEEE Trans. Magn,* Vol.48, No.2, pp.779-782, 2012.

[3] K. Watanabe, F. Campelo, H. Igarashi, “Topology optimization based on immune algorithm and multigrid methods,” *IEEE Trans. Magn.*, Vol.43, No.4, pp.1637–1640, 2007.

[4] J. Moody, C. J. Darken, “Fast learning in networks of locally−tuned processing units”, *Neural Computation*, Vol.1, No.2, pp.281-294, 1989.

[5] K. Watanabe, F. Campelo, Y. Iijima, K. Kawano, T. Matsuo, T. Mifune, H. Igarashi, “Optimization of inductors using evolutionary algorithms and its experimental validation,” *IEEE Trans. Magn.*, Vol.46, No.8, pp.3393–3396, 2010.