Evolutional Design of Waveguide Slot Antenna with Dielectric Lenses

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

[1]Akita National College of Technology, Akita, Akita 011-8511, Japan
[2]Graduate School of Information Science and Technology, Hokkaido University, Sapporo, Hokkaido 060-0808, Japan

This paper reports novel design method of waveguide slot array antenna with dielectric lenses by using the evolutionary optimization. We adopt the micro-genetic algorithm (MGA) with the real-coded gene as the optimization method and the finite-difference time- domain (FDTD) method to evaluate the objective function. The purpose of this study is to establish the design method of the above antenna by optimizing slot length and offset parameters. In the optimization of the antenna aperture distribution, it is shown that the optimized aperture field becomes sufficiently uniform, and the side-lobe levels (SLL) are improved in comparison with those of conventional antennas. Another optimization in which the objective function is evaluated by the array factor controls directly the side-lobe levels, to design low side-lobe antennas. By using the proposed method, the target antenna is optimized to satisfy the given SLL. It is confirmed that the proposed design method is a promising tool for designing the antennas loaded with dielectric materials.

***Index Terms*— dielectric lens, finite-difference time-domain method, micro-genetic algorithm, waveguide slot antennas**

I. INTRODUCTION

To focus the electromagnetic waves over a waveguide slot antenna, we load small spherical dielectric lenses there. It is found that the radiation power is enhanced by loading the dielectric lens for 1-slot case, even when the lens diameter is chosen smaller than the wavelength [1]. To establish the design method of the waveguide slot array antenna loaded with the dielectric lenses is the purpose of this study.

Typical performances required for array antennas are high gain, low side-lobe levels, and low input standing wave ratio (SWR). It is known that the side-lobe level (SLL) is determined by the near-field aperture distribution of array antennas [2][3]. For example, the ratio of the side-lobe level to the main-lobe maximum is less than -13 dB in the case of uniform aperture distribution [3]. Therefore, when we design waveguide slot array antennas, it is necessary to control the slot conditions to realize a desirable aperture distribution.

In the conventional design of waveguide slot array antennas, the slot conditions are determined by calculating the equivalent slot admittance [4]. However, because the equation of the equivalent slot admittance must be derived for every different lens profile, the designers may be required to elaborate mathematical manipulations to evaluate the slot admittance [5]. Additionally, the lens dimensions must be taken into account as the constraint conditions for the design. For the reasons mentioned above, it comes to be difficult to apply the conventional method to the waveguide slot array antenna with the dielectric lenses.

We here apply the micro-genetic algorithm (MGA) to the design of waveguide slot array antennas with the dielectric lenses. MGA is one of the evolutional design methods, and can find nearly optimal solutions with relatively small number of function calls [6]. By introducing the evolutional method into the antenna design, the novel design method is expected to improve the flexibility of the antenna design as compared with the conventional design method.

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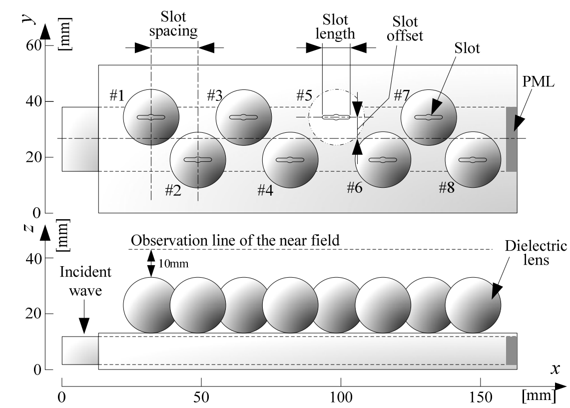

Fig. 1. Analysis model of FDTD method.

We also adopt the finite-difference time-domain (FDTD) method to analyze electromagnetic waves for evaluation of the objective function depends. By combining the high searching ability of MGA and high computational efficiency of FDTD method, the proposed method realizes effective optimizations, which are also applicable for design of other antennas whose electromagnetic properties are not given in closed forms.

This paper reports a novel evolutional design method applied to 8-slot waveguide array antenna loaded with dielectric lenses by using MGA. The above antenna is designed by two different approaches as follows; 1) the optimization of the aperture distribution, 2) the optimization of the side-lobe levels.

II. WAVEGUIDE SLOT ANTENNA

A computational model of the slot array antenna loaded by dielectric lenses is shown in Fig.1. The target antenna consists of RG-52/U waveguide and dielectric lenses. The analysis region consists of 352 × 130 × 110 cells with cell size $\Delta x=\Delta y=\Delta z=0.5$ mm. The perfectly matched layers

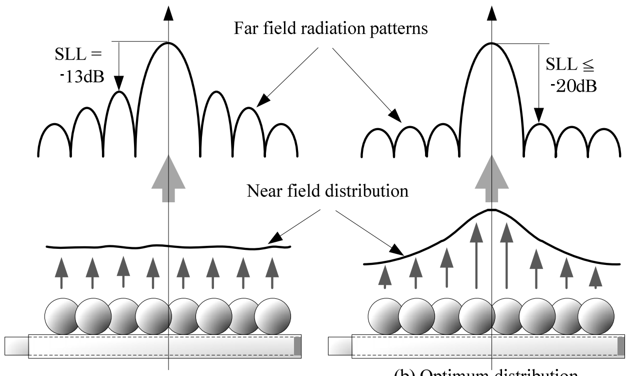

Fig. 2. Relations of radiation patterns and aperture distribution.

(PML) are used as the absorbing boundary conditions. The waveguide is excited by a dominant TE_{10} mode at the incident wall, and terminated at the end wall by a PML condition at $f = 12$ GHz.

The dimension of the spherical dielectric lenses loaded over the slots is 20 mm, which is smaller than the free-space wavelength λ. The lenses are made of polystyrene materials, where the relative permittivity and the loss tangent are supposed to be 2.2 and 10^{-4}, respectively.

The dielectric sphere is divided into the rectangular parallelepiped cells for the FDTD analysis. We assume the calculating error is negligible, because the cell size is small enough compared with the diameter of the lens.

The antenna design parameters usually include the slot length, slot spacing and slot offset. It is well known that the radiation power is determined by the slot length and slot offset, which are shown in Fig.1 [4]. The resonant slot length loaded the proposed dielectric lens is about 10.5 mm [1]. Taking the lens dimensions into account, the slot spacing is fixed at 16.5 mm which is wider than $\lambda_g/2$; λ_g is the waveguide wavelength. As a result, 4.6 degree tilt of beam occurs [4].

As shown in Fig.2, the radiation patterns of the antennas depend on the aperture distribution. The optimization method to control the near-field distribution is examined in the next section.

III. Optimization of Aperture Distribution

A. Micro-Genetic Algorithm

One of the features of MGA is that population size is smaller than the conventional GA [6]. In this paper, the number of population is set to five. We do not adopt the bit-coded gene but the real-coded gene, and perform crossover by using BLX-0.5. Because the antenna parameters are treated as real numbers, the optimization process is free from encoding and decoding. Therefore, it is expected to improve the performance of optimization in the convenience, precision, efficiency and so on.

MGA procedure is shown in flow chart shown in Fig.3. After the individuals are created randomly, MGA repeats the following operation; elitism, crossover with tournament selection and convergence checking. If the individuals converge each other, then the new four individuals except the elite are created randomly.

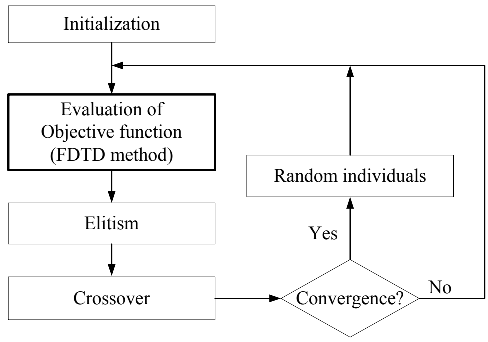

Fig. 3. Flow chart of micro-genetic algorithm.

TABLE I
COMPARISON OF DIFFERENT OBJECTIVE FUNCTIONS

OF		σ [%] Best	σ [%] Average	*VSWR* Best	*VSWR* Average
OF_1	w=1	11.00	12.97	1.002	1.006
	w=0.1	6.46	6.94	1.108	1.139
	w=0.01	5.21	6.11	1.066	1.134
	w=0.001	5.06	7.73	1.084	1.117
	w=0	5.06	7.76	1.084	1.116
OF_2		7.14	8.28	1.054	1.080
Conventional		16.14		1.092	

The objective function is computed by the FDTD method which can calculate the various properties of antenna. The FDTD time step is 9.63×10^{-13} s, and the calculation time is 3,000 time steps. Each individual is ranked by the calculation value of the objective function.

The convergence threshold value β is computed as the difference in the parameters between each slot. To obtain the better local optimum, it is desirable that β is chosen as small as possible. In this paper, β = 0.01 %, because the results do not change for $\beta <$ 0.01 %.

It is important to note that the search space is to be determined appropriately in order to obtain optimal solution. In this paper, the search space is determined as follows; 8.0 to 10.5 mm for slot length, and 3.5 to 8.5 mm for slot offset values. If the search space is too wide, the optimization tends to fall into local minima which do not have good performances.

B. Optimization of aperture distribution

The purpose of the optimization discussed in this section is to realize the desirable aperture distribution. We examine the appropriate objective function as an example of the uniform distribution here.

The proposed optimization method minimizes the difference between the reference field and the electric field on the observation line over the aperture as shown in Fig.1. Furthermore we add the voltage standing wave ratio (*VSWR*) to the objective function in order to reduce the reflection at the input of the waveguide.

TABLE II
OPTIMIZATION RESULTS

Slot No.	#1	#2	#3	#4	#5	#6	#7	#8
OF_1 (w=0.01)								
Slot length [mm]	9.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Slot offset [mm]	4.5	6.5	4.5	7.5	7.0	8.0	7.0	4.5
OF_2								
Slot length [mm]	9.5	10.0	10.0	10.0	10.0	10.0	10.0	9.5
Slot offset [mm]	5.0	6.0	5.0	6.5	7.0	8.0	7.0	7.5

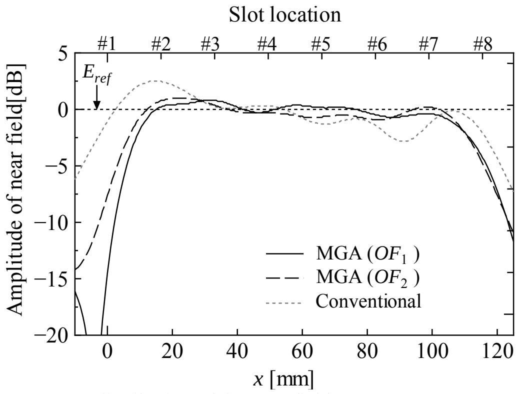

Fig. 4. Aperture distribution of the near-field.

To transform the multi-objective problem into the single objective problem, the objective function OF_1 is expressed by

$$OF_1 = \frac{\sigma}{E_{ref}} + VSWR \times w \qquad (1)$$

The first term expresses the standard deviation σ for the reference electric field E_{ref}, w of the second term is a weighting constant. OF_1 defined in (1) is minimized with respect to the optimization parameters mentioned above, subjected to the constraint that the adjacent lenses do not touch each other.

For a comparison, the optimization is performed by using the different objective function OF_2 which is defined as

$$OF_2 = \frac{\sigma}{E_{ref}} + \text{penalty} \qquad (2a)$$

$$\text{penalty} = \begin{cases} \frac{VSWR - 1.1}{1.1}, & \text{if } VSWR > 1.1 \\ 0, & \text{otherwise} \end{cases} \qquad (2b)$$

Table I shows the optimization. The MGA processes are performed for 800 generations. Because the population size of MGA is small, it is predicted that the iterations of MGA tend to increase as compared with that of the conventional GA. All slots of the conventional antenna have the same dimension; slot length and slot offset are 10.5 mm and 7.5 mm respectively. From the results, the standard deviation converges to around 5%.

C. Results

The slot dimensions of the optimized antenna are shown in Table II. From the obtained parameters, the near-field distribution on the observation line and the far-field radiation patterns are calculated by the FDTD method.

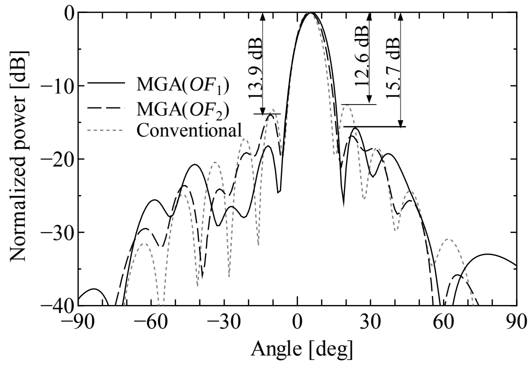

Fig. 5. *H*-plane far-field radiation patterns.

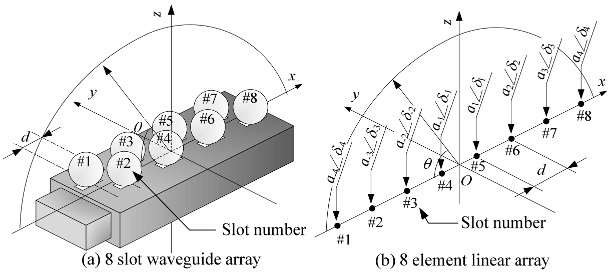

Fig. 6. Relations between the waveguide array and the linear array for even number slot.

Fig.4 shows that the aperture field distribution of the optimized antenna is much more uniform compared with that of the conventional antenna. Then, σ is 5.21 % for OF_1 and 7.14% for OF_2. The side-lobe levels of the optimized antenna are also found to be improved in comparison with those of the conventional antenna as shown in Fig.5.

It is shown here that we are able to determine the proper parameters to produce a uniform distribution by using the proposed design method in either objective function.

IV. LOW SIDE-LOBE ANTENNA DESIGN

To design the low side-lobe antennas, it is generally required to control precisely the aperture distribution such as the Taylor or the Dolph-Tchebyscheff distribution [3]. In contrast, we propose the direct control method of the side-lobe levels of the antenna in this section.

A. Array factor

The directivity of the array antennas can be derived from the array factor $AF(\theta)$. It is well known that The radiation patterns of the array antennas is estimated from the product of the array factor $AF(\theta)$ and the element patterns $D_e(\theta)$ which is the radiation patterns from a single element [3]. Fig.6 shows the relations between the slot of the waveguide array antenna and the element of the linear array for the even number N, where N is the number of the element. The array factor is defined as follows:

$$AF(\theta) = \sum_{n=1}^{m} \left\{ a_n e^{j(\delta_n + \frac{2n-1}{2} k_0 d \cos\theta)} + a_{-n} e^{j(\delta_{-n} - \frac{2n-1}{2} k_0 d \cos\theta)} \right\} \qquad (3)$$

where a_n is the amplitude of the slot and δ_n is the phase difference form the origin. Also, k_0 is the wave number ($=2\pi/\lambda$), d is the slot spacing and $m = N/2$.

TABLE III
OPTIMIZATION RESULTS

Slot No.	#1	#2	#3	#4	#5	#6	#7	#8
Slot length [mm]	8.5	8.5	9.5	9.5	9.5	9.5	8.0	8.0
Slot offset [mm]	4.0	6.5	6.0	7.0	7.0	5.5	6.5	5.0
Array factor								
a_n	0.57	0.85	1.10	1.23	1.23	1.03	0.79	0.62
δ_n [rad]	-1.41	-1.10	-0.45	-0.25	0.25	0.59	0.72	1.05

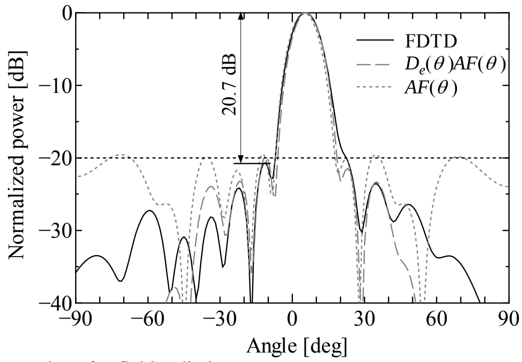

Fig. 7. *H*-plane far-field radiation patterns.

If all slots are provided in phase, equation (3) becomes simpler by ignoring the term of δ_n. However, because the slot spacing is not $\lambda_g/2$, the phase of each slot is slightly out of phase.

The SLL is defined as the ratio for the main-lobe level. As varying the angle θ form 0 to 180 degree, the SLL is calculated from (3) according to the following procedure; 1) the calculation of the absolute value of the array factor, 2) the definition of the maximum value of the array factor as the main-lobe level, 3) the calculation of the SLL as the ratio for the main-lobe level.

B. Optimization of side-lobe level

We introduce an objective function to design low side-lobe antennas in this section. To control the side-lobe level directly, the proposed design method minimizes SLL which is calculated by the array factor.

The amplitude a_n and the phase difference δ_n of the array factor are calculated by the FDTD method as follows: a_n is the root mean square value of the electric field on the slot, and δ_n is the phase difference from the origin; a center of #4 and #5 in Fig.6.

The objective function for a low side-lobe antenna design is defined as follows:

$$OF = \text{penalty}_{\text{SLL}} + \text{penalty}_{VSWR} \quad (4a)$$

$$\text{penalty}_{\text{SLL}} = \begin{cases} \dfrac{SLL_{\max} - 0.1}{0.1}, & \text{if } SLL_{\max} > 0.1 \\ 0, & \text{otherwise} \end{cases} \quad (4b)$$

$$\text{penalty}_{VSWR} = \begin{cases} \dfrac{VSWR - 1.1}{1.1}, & \text{if } VSWR > 1.1 \\ 0, & \text{otherwise} \end{cases} \quad (4c)$$

where $SLL_{\max}$ is the maximum of the SLLs. The goals of $SLL_{\max}$ and *VSWR* are set as 0.1 (= -20 dB) and 1.1 respectively. The MGA processes are performed for 1,000 generations.

C. Results

The optimization results are shown in Table III, where the amplitude a_n is normalized by the reference field. Fig.7 shows the far-field radiation patterns which are computed with the optimized parameters. From the results, the optimized antenna satisfies the given condition that SLL is -20 dB. Then the side-lobe levels of the array factor are less than almost given condition. Also, it is shown that the antenna patterns $D_e(\theta)AF(\theta)$ coincide well with the FDTD results. In this optimization, the magnitude of the main-lobe is lower than the expected value. However, the proposed method is capable of maximizing the output power of the antenna by increasing the whole slot power. Also, to design in case of large number of the antenna element [7], the improvement of the proposed design method is necessary.

It is found that design of the low side-lobe antenna is possible by the proposed method. By modifying the objective function, the proposed method will be applied to the optimization for the null point and the beam tilt angle.

V. CONCLUSION

We have demonstrated that the evolutional design method by using MGA is a promising and efficient tool for optimizing waveguide slot array antennas loaded with dielectric lenses. The proposed method is very useful as one of the antenna design method. In particular, it is suitable to design the antennas which are difficult to obtain the exact solutions, for instance, lens loaded antenna, the conformal array antenna and so on.

Studies to be done further include; 1) optimization to realize arbitrary distribution, 2) control of the null point and the beam width of the main-lobe, 3) maximization of the antenna gain, 4) speed up of computation.

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