Optimization of Radiation Pattern for Narrow-wall Slotted Waveguide Arrays Using HOBBIES

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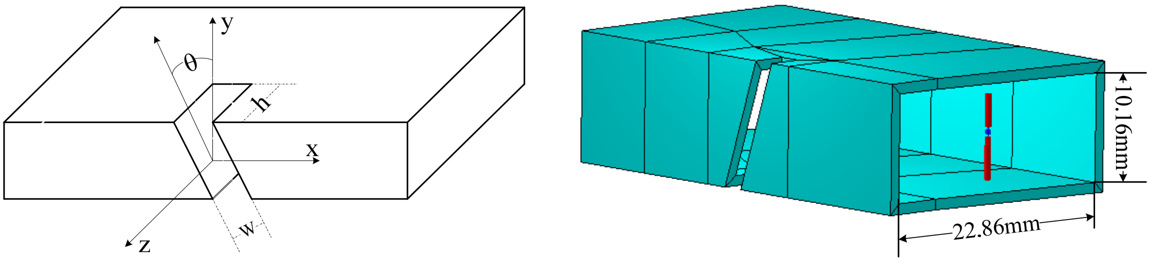
1. Introduction

Narrow-wall inclined slots (Fig. 1) are commonly used in practical radar applications. There have been a lot of publications in the past on the analysis and design of these types of slotted waveguide antennas [1]–[3]. These works have focused on analyzing the structure using different numerical methods, but there is no publication discussing the optimization of the slotted waveguide, as the structural meshing of the slotted waveguide will generate a large number of unknowns and it is very time consuming to analyze this structure. This is still an issue with the Method of Moments technique to analyze this structure on a PC due to the limitation of the computing power. Even with the help of high performance clusters, it is not an easy task, not to mention optimizing the entire array, since it contains so many variables. This necessitated the need for a reliable optimization tool to handle a problem with a large number of variables to optimize. And this paper is motivated by this need, and focuses on the optimization of radiation patterns of narrow-wall slotted waveguide arrays.

In this paper, the commercial software HOBBIES (Higher-Order Basis Based Integral Equation Solver) [4]-[5] will be used to analyze the structure. HOBBIES is an out-of-core parallel solver that can be executed across multiple platforms to solve complicated EM problems and it provides solutions based on the Method of Moments. By using HOBBIES, several PCs can be combined to form a parallel computing platform, thus being able to generate solutions for very complex problems. Several optimization algorithms are available within HOBBIES, such as BOBYQA, particle swarm optimization, Simplex algorithm. In this paper, the BOBYQA has been used to optimize the radiation pattern of the slotted waveguide structure. BOBYQA is one of the best state-of-the-art derivative free optimization methods dealing with hundreds of variables proposed by M. J. D. Powell in 2009. Details of this algorithm are in [6].

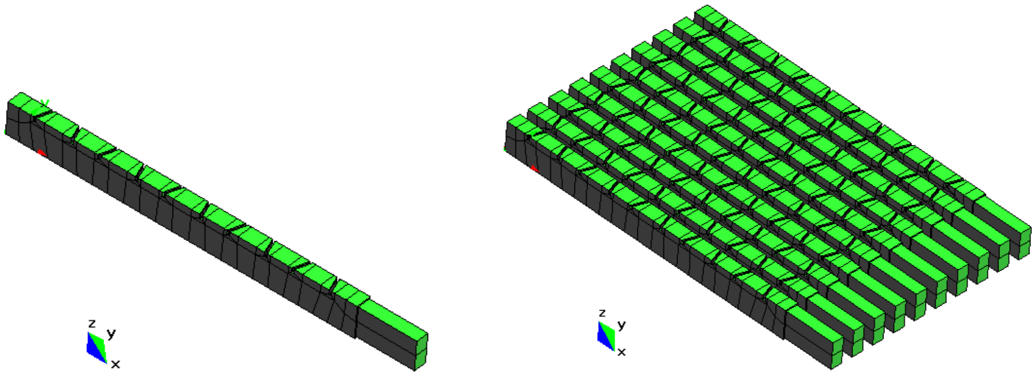
2. Antenna Geometry

The slotted waveguide antenna array is formed by ten single slotted waveguides, shown as Fig. 2(b), with the distance between two adjacent waveguide centers of 20.00 mm. For each single waveguide, there are 10 narrow wall slots, as shown in Fig. 2(a), with dimensions of 22.86mm×10.16 mm, and with a wall thickness of 1.00 mm. The whole length of the waveguide is 266.58 mm. The working frequency of interest is 9.375 GHz. A small dipole is used as the excitation source inside each waveguide, as depicted in Fig. 1(b). Fig. 1(a) gives the geometry of the inclined slot. The inclined angle of the slots is set to be θ, and the cutting depth and width of slots are h and w, respectively. From array theory, a 20 dB Taylor distribution is used in the feeding of the waveguide array to achieve the desired radiation pattern. And there's a 0.9 π phase difference between the feeds of the adjacent radiating waveguides.



(a) (b)

Fig. 1 A narrow wall inclined slot: (a). Geometry of an inclined slot; (b). Feeding inside the waveguide



(a) (b)

Fig. 2 (a) A single waveguide with narrow wall inclined slots; (b) A 10-elements waveguide array

3. Numerical Results and Discussions

Our goal is to optimize the radiation pattern of the slotted waveguide array. The optimization criteria are then set for a higher main lobe gain along +z direction and better side lobe levels (SLL). The fitness function is then set to be the differences between the objective pattern and the computed pattern, and has the following formulation.

$$FF(\underline{x}) = \sum_{i=1}^{n} \frac{w_i}{\alpha_i} f_i(\underline{x}) \ , \ i = 1, 2, \ldots, n \tag{5}$$

$$f_i(\underline{x}) = \sqrt{\frac{1}{num} \sum_{k=1}^{num} (G_k(\underline{x}) - G_0)^2} \tag{6}$$

where FF is the total fitness value and f_i is the fitness value for the i-th criterion. The total fitness value is the addition of fitness value for each single criterion which is normalized and weighted. The calculation of fitness value for the i-th criterion is outlined in equation (6). And $\underline{x}$ are the variables to be optimized, w_i and α_i being the weight and the normalization factor for the i-th criterion, $G_k(\underline{x})$ being the obtained gain of the slotted waveguide array along the k-th angle (given in dB), and G_0 is the objective gain at the k-th angle (given in dB). n is the number of criteria, and each criterion is associated with a normalization factor and a weight. When the fitness function is decreased, the computed radiation pattern becomes closer to the objective pattern. If the fitness function results in a value of zero, our goal is achieved.

For this slotted waveguide array example, the inclined angle θ and the cutting depth h of each slot are variables to be optimized. There are 10 slots on the wall of the single waveguide, and each single waveguide has the same dimensions except with opposite inclined angles, so that a total of 20 variables are to be optimized. For optimization, all the θ have the initial value of 17.68 and all the h have the initial value of 3.30 [7].

The waveguide array is meshed and executed on a small cluster (IBM System X3500 Type 7977) with 2 nodes and each node has a dual quad core processor. There are more than 34,000 unknowns after the array is meshed. It takes the cluster fifteen minutes to finish one simulation of the waveguide array.

We have applied the BOBYQA algorithm for the optimization of the radiation pattern for this large array. The optimized dimensions of the slots are given in Table 1. The convergence curve is shown in Fig.3. The fitness value of every simulation call was recorded and plotted in the figure. It is shown that after about 60 simulation calls, the curve starts to change mildly and after about 100 simulation calls the computed results start converging. Considering the 20 variables to be optimized, this speed of convergence is fast.

Table 1: Dimensions of the slots after optimization

Element number	1	2	3	4	5	6	7	8	9	10
Inclined angle θ (°)	17.11	17.07	17.35	17.73	17.83	18.43	17.70	18.07	17.64	17.86
Cutting depth h (mm)	3.30	3.05	3.18	3.18	2.96	3.09	3.31	3.88	3.74	3.55

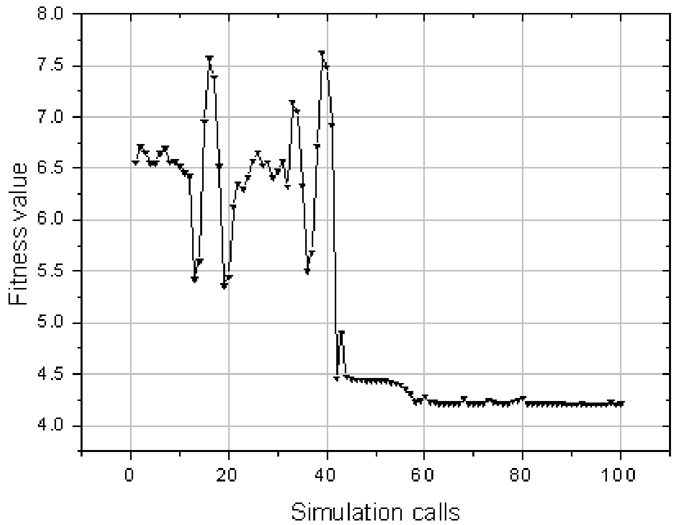
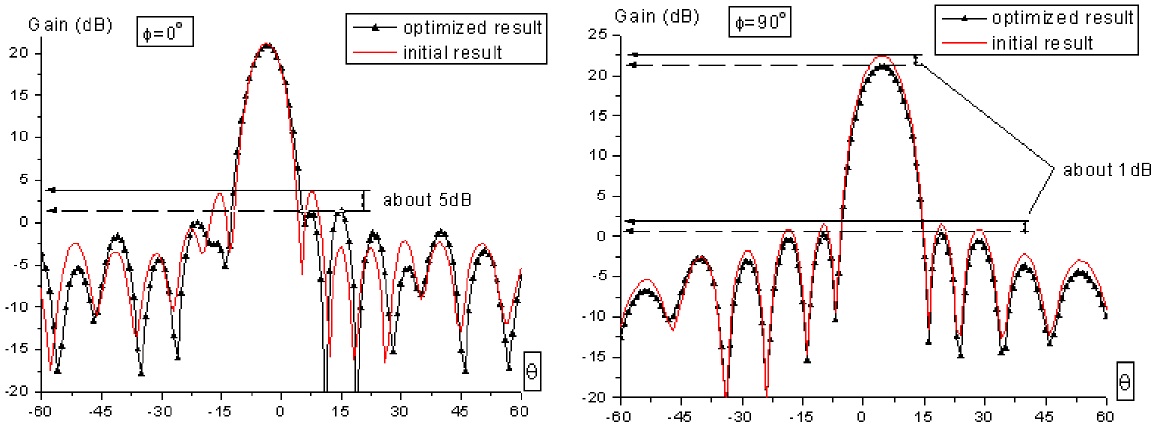


Fig. 3 Convergence curve for the waveguide array optimization

The radiation patterns of the slotted waveguide array are shown in Fig. 4. The red smooth curve is the initial radiation pattern, whereas the black curve with triangles is the optimized pattern. Due to the phase difference between the feeds, the directions of the main lobe in the E-plane and H-plane is 5 ° away from the +z direction. In Fig.4 (a) the plot shows the E-plane pattern remains similar main lobe after the optimization, whereas the largest side lobes at θ = -15° and θ = 8° are suppressed by about 5 dB. The solid arrow line and dash arrow line mark the highest side lobe for the initial result and optimized result in the figure, respectively. It is easy to see that the side lobe level (SLL) performance improved about 5 dB.

Fig.4 (b) plots the H-plane pattern, similarly, the solid and dash line shows the highest side lobe and also the main lobe value for the radiation pattern before and after optimization, respectively. We can see that both the main lobe and the largest side lobe decrease by about 1 dB after optimization, so the SLL remains the same. In summary, the radiation pattern has been improved in the E plane whereas in the H plane it relatively remains at the same level.



(a) (b)

Fig. 4 Radiation pattern comparison of the slotted waveguide array: (a). E plane; (b). H plane

5. Conclusions

The antenna along with its variables is optimized for a highly complicated electromagnetic structure containing numbers of variables for optimization. Narrow-wall slotted waveguide arrays have been analyzed but no optimization study has been presented in the literature. One optimization example of the slotted waveguide is presented in this paper, and the radiation patterns show improvement after the optimization. A new optimization algorithm, BOBYQA, which requires no derivative information of the function, is used in this paper to seek the minimum of the function with 20 variables. The convergence curve is given and it shows fast convergence of the algorithm for the slotted waveguide example. Future study will involve algorithm improvement and optimization of larger slotted waveguide arrays in radar applications.

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