Rectangular Waveguide Design Optimization by Sequential Nonlinear Programming and Genetic Algorithm

Meijiao Lin[1], Xin Zhang[1(✉)], Yang Li[1], and Zhou Wu[2]

[1] Tianjin Key Laboratory of Wireless Mobile Communications and Power Transmission, Tianjin Normal University, Tianjin 300387, China
1648016529@qq.com, ecemark@tjnu.edu.cn, liyang_tongxin@163.com

[2] School of Automation, Chongqing University, Chongqing 400044, China
zhouwu@cqu.edu.cn

Abstract. Rectangular waveguide is a common metal waveguide with simple fabrication, low loss and dual polarization. It is often used in antenna feeders requiring dual polarization mode, and also widely used in various resonators and wavelength meters. This paper attempts to design, simulate and optimize rectangular waveguide. By setting the length, width and height of rectangular waveguide, the required rectangular waveguide is designed. The resonant frequency of rectangular waveguide is setting to 9.25 GHz. Moreover, the input return loss is required to be as small as possible. After satisfying the requirements, sequential nonlinear programming and genetic algorithm are used to optimize both voltage standing wave ratio and normalized impedance matching. Simulation results show that the proposed method is able to accomplish the optimal design of rectangular waveguide.

Keywords: Rectangular waveguide · Optimal design · Sequential nonlinear programming · Genetic algorithm

1 Introduction

Rectangular waveguide is a kind of metal tube with rectangular cross section [1]. If the inner conductor of the coaxial line is removed, under certain conditions, electromagnetic energy can also be transmitted in the rectangular space surrounded by the outer conductor, which is the rectangular waveguide [2]. Rectangular waveguide has the advantages of simple fabrication, low loss and bipolarity [3]. They are usually used in antenna feeders requiring bipolar mode, and are also widely used in various resonators and wavelength meters. They are commonly used conventional metal waveguide [4]. Rectangular waveguide cannot propagate Transverse Electric and Magnetic Field, but can only propagate Transverse Electric or Transverse Magnetic waves [5].

As a global method, genetic algorithm [6] can use the idea of genetics to find the optimal value without considering the specific characteristics of the objective function to be optimized [7]. The objective function of antenna array optimization has the

X. B. Zhai et al. (Eds.): MLICOM 2019, LNICST 294, pp. 101–108, 2019.
https://doi.org/10.1007/978-3-030-32388-2_9

characteristics of complex shape and many peaks, so it is more appropriate to use genetic algorithm to optimize the antenna array [8].

Similar to quasi-Newton method, sequential nonlinear programming algorithm is suitable for solving low-noise problem of objective function. Noise filtering is introduced in sequential nonlinear programming, which can reduce the influence of noise appropriately. Sequential nonlinear programming uses response surface modeling technology to estimate the value of the objective function more accurately. Compared with quasi-Newton method, sequential nonlinear programming has faster convergence speed. In addition, sequential nonlinear programming allows the use of non-linear constraints, which is more widely used than Newton's method and pattern search method [9].

2 Waveguide Model and Optimization Model

2.1 Waveguide Model

The rectangular waveguide model consists of two cuboid models. One is used to simulate a rectangular waveguide with a cross-section size of 0.4 in. × 0.9 in., and the other is used to simulate a free space with a cross-section size of 0.5 in. × 1.0 in. The height of both the simulated rectangular waveguide and the cuboid in the free space is 1 in., as shown in Fig. 1.

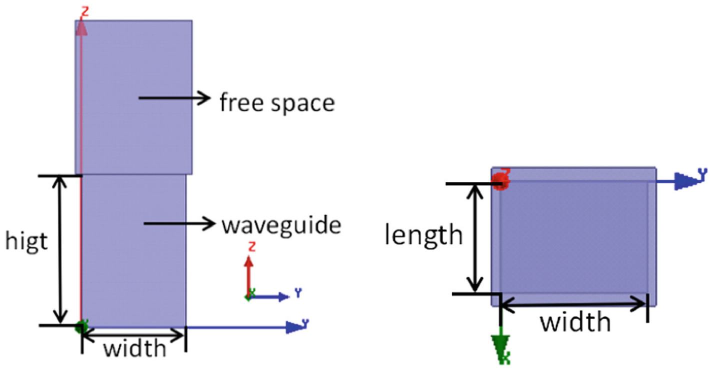

Fig. 1. Rectangular waveguide model.

2.2 Optimization Model

The parameter scanning analysis function is used to analyze the relationship between the resonant frequency points and the length, width and height of the rectangular waveguide. The design of rectangular waveguide is expressed as (1).

$$
\begin{aligned}
\min \quad & InputReturnLoss(l, w, h) \\
s.t. \quad & Frequency(l, w, h) = 9.25 \text{ GHz} \\
& \text{Impedance}(l, w, h) = 50\ \Omega \\
& 0.2 \leq l \leq 0.6 \\
& 0.7 \leq w \leq 1.1 \\
& 0.8 \leq h \leq 1.2
\end{aligned} \tag{1}
$$

where variables l, w, and h are respectively the length, width and height of rectangular waveguide. The objective is to minimizing input return loss of waveguide under resonant frequency and impedance constraints. The ranges of variables l, w, and h are set based on empirical experience.

Then, the optimal design is carried out by Sequential Nonlinear Programming to optimize the length, width and height of the rectangular waveguide so that the resonant frequency of the antenna falls to 9.25 GHz.

3 Optimized Model Analysis and Discussion

3.1 Genetic Algorithm

S11 represents the echo loss, that is, how much energy is reflected back to the source, the smaller the value, the better. Length optimization ranges from 0.2 to 0.6 in., Width optimization ranges from 0.7 to 1.1 in. and High optimization ranges from 0.8 to 1.2 in.

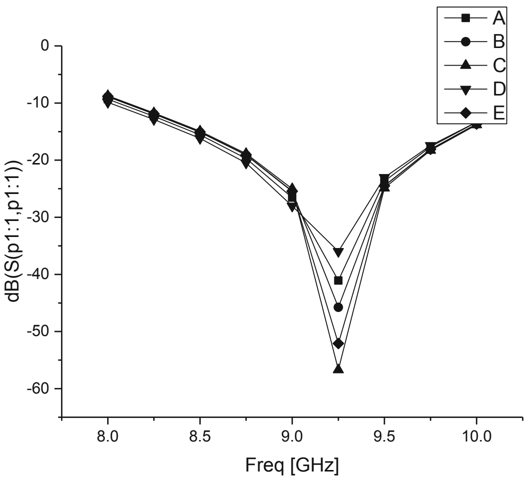

Fig. 2. Echo loss graphs of different variables found by genetic algorithm.

In Fig. 2, the five graphs labeled from A to E are as follows.

A: High = 0.903066 in., Length = 0.584262 in., Width = 0.782867 in.
B: High = 1.071951 in., Length = 0.584290 in., Width = 0.779443 in.
C: High = 1.124028 in., Length = 0.584294 in., Width = 0.777727 in.
D: High = 1.093114 in., Length = 0.584325 in., Width = 0.787910 in.
E: High = 0.998307 in., Length = 0.584334 in., Width = 0.778503 in.

From Fig. 2, when Length = 0.584294 in., Width = 0.777727 in. and High = 1.124028 in., the lowest point of S11 curve is above 9.25 GHz and the lowest point is −56.7140 dB. Therefore, the rectangular waveguide is set to change its size, and the voltage rejection ratio and the normalized matched impedance of the rectangular waveguide are analyzed.

Voltage Standing Wave Ratio (VSWR)

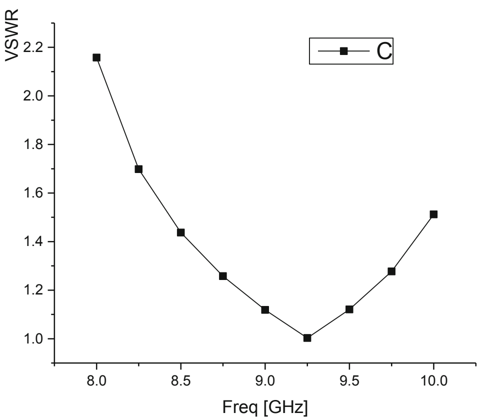

Fig. 3. Voltage standing wave ratio of the optimal result found by genetic algorithm.

Figure 3 is analyzed based on the optimal result found by genetic algorithm. As shown in Fig. 3, the voltage standing wave ratio is 1.002923, close to 1. At this time, the impedance of the feeder and antenna is highly matched. At this time, all the high frequency energy is radiated by the antenna, and there is no reflection loss of energy.

Normalized Matching Impedance

As shown in Fig. 4, normalized matching impedance [10] is 1.0013, close to 1. The number is normalized according to 50 Ω. The impedance obtained by genetic algorithm is 50.065 Ω. It is proved that the impedance matching is good at this time, which is consistent with the results of VSWR mentioned above.

3.2 Sequential Nonlinear Programming

Sequential nonlinear programming is used to solve rectangular waveguide model (1). The parameter settings and simulation environment are the same as Sect. 3.1.

In Fig. 5, the five graphs labeled from A to E are as follows.

A’: High = 1.088738 in., Length = 0.586402 in., Width = 0.774999 in.
B’: High = 1.080961 in., Length = 0.586469 in., Width = 0.775927 in.
C’: High = 1.085099 in., Length = 0.586591 in., Width = 0.775738 in.
D’: High = 1.084712 in., Length = 0.586621 in., Width = 0.775624 in.
E’: High = 1.085877 in., Length = 0.586668 in., Width = 0.775699 in.

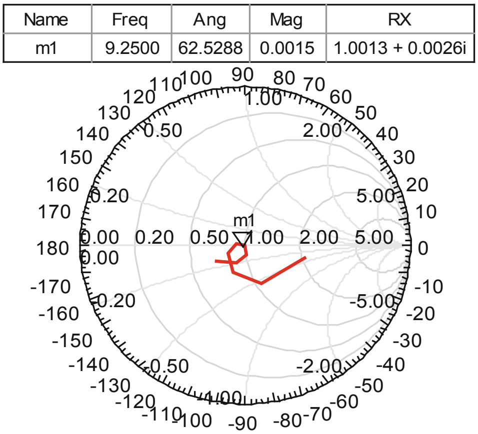

Fig. 4. Smith chart of the optimal result found by genetic algorithm.

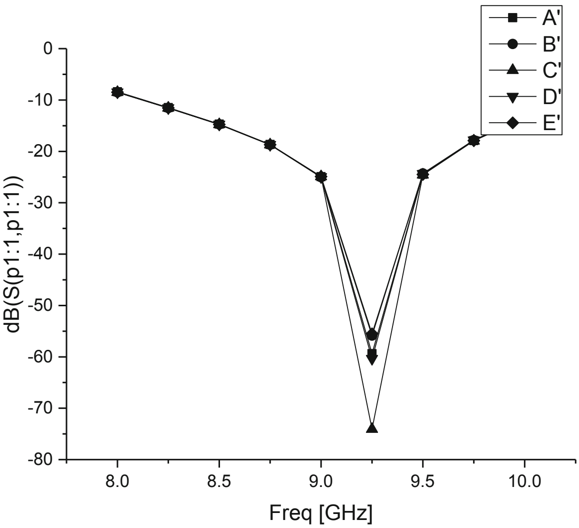

Fig. 5. Echo loss graphs of different variables found by sequential nonlinear programming.

From Fig. 5, when Length = 0.586591 in., Width = 0.775738 in., High = 1.085099 in., the lowest point of the S11 curve is above 9.25 GHz and the lowest value is −74.0596 dB. Therefore, the rectangular waveguide is set to change its size, and the voltage rejection ratio and the normalized matched impedance of the rectangular waveguide are analyzed.

Voltage Standing Wave Ratio

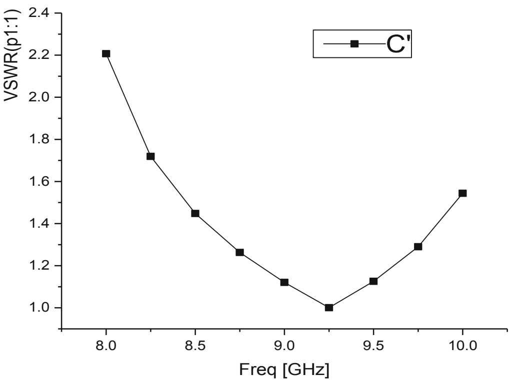

Fig. 6. Voltage standing wave ratio of the optimal result found by sequential nonlinear programming.

Figure 6 is analyzed based on the optimal result found by genetic algorithm. As shown in Fig. 6, the voltage standing wave ratio is 1.000396, close to 1. At this time, the impedance of the feeder and antenna is highly matched. At this time, all the high frequency energy is radiated by the antenna, and there is no reflection loss of energy.

Normalized Matched Impedance

As shown in Fig. 7, the normalized matching impedance is 1.0003, close to 1. The number is normalized according to 50 Ω. The impedance obtained by sequential nonlinear programming is 50.015 Ω. It is proved that the impedance matching is good at this time, which is consistent with the results of VSWR mentioned above.

3.3 Comparison of Genetic Algorithm and Sequential Nonlinear Programming

Comparing the two optimization methods, sequential nonlinear programming is better than genetic algorithm in terms of antenna impedance matching. Moreover, impedance of the solution found by sequential nonlinear programming matches 50 Ω better than impedance of the solution found by genetic algorithm. Furthermore, the simulation time of sequential nonlinear programming is less than the time of genetic algorithm. This is because genetic algorithm is generally used in antenna arrays with complex shape and multi-peak characteristics of objective function, which is not applicable to simple antenna model. Therefore, sequential nonlinear programming is more suitable to solve the rectangular waveguide model (1) than genetic algorithm.

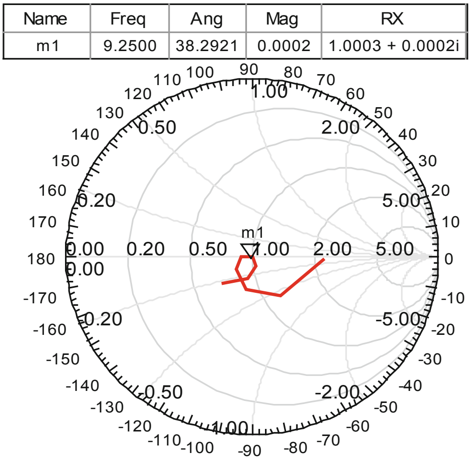

Fig. 7. Smith chart of the optimal result found by sequential nonlinear programming.

4 Conclusion

This paper focuses on the optimization design of rectangular waveguide based on genetic algorithm and sequential nonlinear programming. By setting the length, width and height of rectangular waveguide as variables, a rectangular waveguide model is designed to minimize input return loss of radiation direction at 9.25 GHz frequency. Then two methods are used to solve the optimization model. Based on simulation results, sequential nonlinear programming attains better solution and costs less computational time than genetic algorithm.

Acknowledgment. This research was supported in part by the National Natural Science Foundation of China (Project No. 61603275, 61601329, 61803054), the Tianjin Higher Education Creative Team Funds Program, the Basic Research and Frontier Exploration Project (Project No. cstc2018jcyjAX0297), the Fundamental Research Funds for the Central Universities (Project No. 2019CDQYZDH030), and the Doctor Fund of Tianjin Normal University (Project No. 52XB1905).

References

1. Deslandes, D., Wu, K.: Integrated microstrip and rectangular waveguide in planar form. IEEE Microw. Wirel. Compon. Lett. **11**(2), 68–70 (2001)
2. Sun, D., Xu, J.: Rectangular waveguide coupler with adjustable coupling coefficient using gap waveguide technology. Electron. Lett. **53**(3), 167–169 (2017)

3. Sutthaweekul, R., Tian, G.Y.: Steel corrosion stages characterization using open-ended rectangular waveguide probe. IEEE Sens. J. **18**(3), 1054–1062 (2018)
4. Filins'kyy, L.A.: Microwave propagation in specimens of foam materials located in rectangular waveguide. In: 6th International Conference on Ultrawideband and Ultrashort Impulse Signals, pp. 108–110. IEEE, Sevastopol (2012)
5. Zhang, Y., Krasheninnikov, S.I.: Electron dynamics in the laser and quasi-static electric and magnetic fields. Phys. Lett. A **382**(27), 1801–1806 (2018)
6. Goldberg, D.: Genetic Algorithms in Search, Optimization, and Machine Learning. Addison-Wesley, Boston (1989)
7. Horton, P., Jaboyedoff, M., Obled, C.: Global optimization of an analog method by means of genetic algorithms. Mon. Weather Rev. **145**(4), 1275–1294 (2017)
8. Coccioli, R., Pelosi, G., Selleri, S.: Optimization of bends in rectangular waveguide by a finite-element genetic-algorithm procedure. Microw. Opt. Technol. Lett. **16**(5), 287–290 (1997)
9. Optimization Methods. http://blog.sina.com.cn/s/blog_4bc5db550100prev.html. Accessed 27 Feb 2019
10. Williams, D.F., Jargon, J., Arz, U.: Rectangular-waveguide impedance. In: 85th Microwave Measurement Conference (ARFTG), pp. 1–5. IEEE, Phoenix (2015)