

# Fabrication and Evaluation of a Waffle Type Waveguide for Ku-Band Application

Kenji Itagaki and Sang-Seok Lee\*

Graduate School of Engineering, Tottori University, Japan

\*sslee@eecs.tottori-u.ac.jp

**Abstract**—In this paper, we propose a waffle type waveguide for Ku-band application. For the first time, we fabricated and evaluated the waffle type waveguide. The waffle type waveguide consists of rectangular structure and waffle type structure for electromagnetic wave transmission and attenuation, respectively. Bosses are periodically arrayed horizontally in waffle type structure and they are confronted vertically each other with air gap, which act as a low pass filter. The waveguide operation in Ku-band was confirmed by finite element simulation. Moreover, the waveguide firstly fabricated by machining was evaluated by S-parameter measurements. As a result, the measurement results well agreed with the simulation ones. We firstly and successfully verified the operation of the waffle type waveguide. We also achieved low transmission loss, and low reflection below 20 dB over wide frequency range from 15.2 GHz to 23.0 GHz which corresponds to a 40.8% fractional band width.

**Keywords** — waffle type, Ku-band, transmission, low pass filter.

## I. INTRODUCTION

Microwave circuits are used for various applications such as communication, imaging, remote sensing and radar systems. Its application is paid attention from various fields. Among microwave circuits, in this study, we focus on a waveguide that is a basic and one of important microwave circuit components.

Flat transmission lines such as substrate integrated waveguide (SIW) [1] and MEMS transmission lines such as hollow waveguide [2,3] using micromachining technology have been proposed to obtain high performance transmission lines. In particular, rectangular waveguide which is one of the transmission lines is widely used as an electromagnetic wave transmission component in microwave circuits due to fabrication easiness. However, it has disadvantage that its characteristics are influenced easily by fabrication accuracy, assembly accuracy, inner surface roughness, and inner surface flatness. To reduce such kinds of influences, a waffle type waveguide that is one of non-contact waveguide was proposed [4]. The basic idea of the waffle type waveguide is applying a non-contact filter such as a corrugate structured filter [5] to the waveguide. The waffle type waveguide consists of rectangular structure and waffle type structure for electromagnetic wave transmission and attenuation, respectively. The waffle type structure acts as a low pass filter, which cuts off frequencies lower than to be transmitted frequencies. Consequently, electromagnetic waves having higher frequencies than cut off frequency are confined in rectangular part and transmitted.

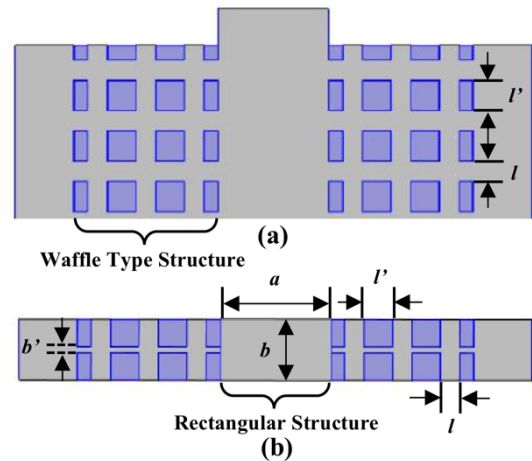


Fig.1. Schematic views of waffle type waveguide: (a) top view and (b) cross sectional view of the waveguide. Blue boxes represent bosses in waffle type structure, which are separated with a distance  $l$ .

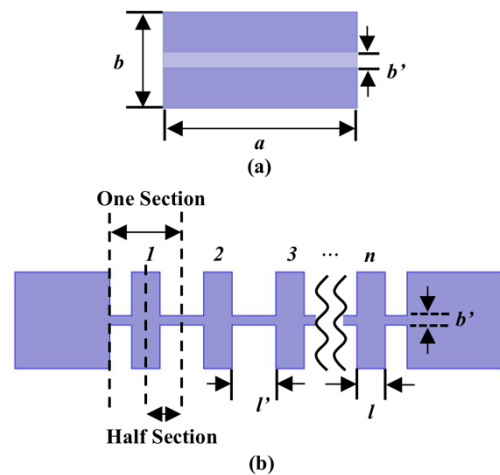


Fig. 2. Schematic views of corrugated filter: (a) end view and (b) side view.

In this paper, we propose a waffle type waveguide for Ku-band application. To verify our designed a novel waffle type waveguide, for the first time, we fabricated and evaluated it.

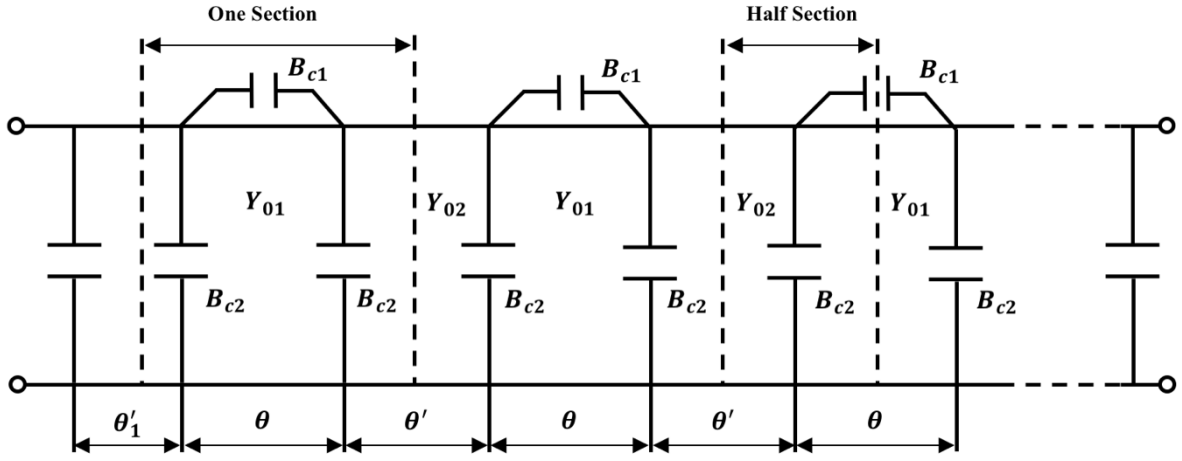


Fig. 3. Distributed constant equivalent circuit of the corrugated filter.

## II. DESIGN OF WAFFLE TYPE WAVEGUIDE

A schematic view of waffle type waveguide is shown in Fig. 1. Two waffle type structures acting as a low pass filter are placed on both sides of rectangular structure for electromagnetic wave transmission. In each waffle type structure, bosses are periodically arrayed horizontally with a gap  $l$  and a width  $l'$ . Moreover, they are confronted vertically each other with a gap  $b'$  simultaneously. The width and height of rectangular part are  $a$  and  $b$ , respectively. At boundary surface between waffle type structure and rectangular part, virtual impedance wall was taken into account. The virtual impedance wall is acted like the side wall of usual rectangular waveguide.

To determine each dimension of 2-dimensional periodic waffle type structure, first, we designed 1-dimensional periodic corrugated filter, and then, we modified dimensions obtained for corrugated filter. The structure of a corrugated filter, which is 1-dimensional periodic structure, is shown in Fig. 2. In addition, the distributed constant equivalent circuit of the corrugated filter is shown in Fig. 3. In Fig. 3,  $Y_{01}$  and  $Y_{02}$  are normalized characteristic admittances as follows:

$$Y_{01} = 1, Y_{02} = \frac{1}{\delta}, \delta = \frac{b'}{b}. \quad (1)$$

Moreover, electrical lengths  $\theta$  and  $\theta'$  are represented as follows:

$$\theta = \frac{2\pi l}{\lambda_g}, \theta' = \frac{2\pi l'}{\lambda_g}, \quad (2)$$

where  $\lambda_g$  is the wavelength in the waveguide, which is given by as follows:

$$\lambda_g = \frac{\lambda}{\sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}}, \quad (3)$$

where  $\lambda$  is the wavelength in free space.

$B_{c1}$  and  $B_{c2}$  are capacitive normalized susceptances generated by the electric field concentrated in each section as follows:

$$B_{c1} \approx \frac{2}{\lambda_g} \sum_{n=1}^{\infty} \frac{1}{n} \frac{\text{csch} \frac{2n\pi l F_n}{b}}{F_n}, \quad (4)$$

$$B_{c2} \approx \frac{2}{\lambda_g} \left\{ \ln \frac{1}{\delta} - 0.338 + \sum_{n=1}^{\infty} \frac{1}{n} \left( \frac{\tanh \frac{n\pi l F_n}{b}}{F_n} - 1 \right) \right\}, \quad (5)$$

where

$$F_n = \sqrt{1 - \left(\frac{b}{n\lambda_g}\right)^2}. \quad (6)$$

In corrugated filter, characteristic admittance  $Y_{02}$  of high impedance section with electrical length  $\theta$ , and characteristic admittance  $Y_{01}$  of low impedance section with electrical length  $\theta'$  are connected alternately.

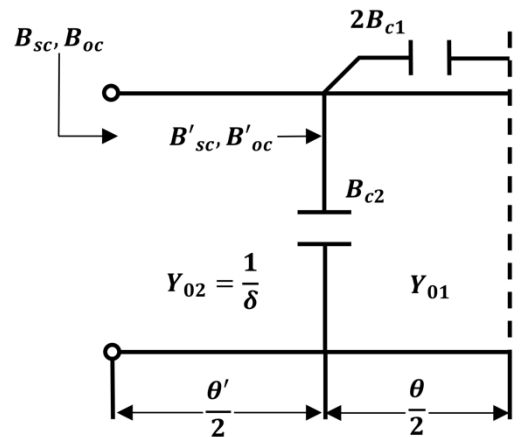


Fig. 4. Normalized half model of the corrugated filter equivalent circuit.

For basic mode analysis of the corrugated filter, we used a half model of the distributed constant equivalent circuit, which is shown in Fig. 4.

Susceptances of the open termination and the short termination in half equivalent circuit model are denoted as  $B_{oc}$  and  $B_{sc}$ , respectively and they represented as follows:

$$B_{oc} = \frac{1}{\delta} \cot \frac{\theta'}{2} \cdot \frac{\frac{1}{\delta} \tan \frac{\theta'}{2} - B'_{oc}}{\frac{1}{\delta} \cot \frac{\theta'}{2} - B'_{oc}}, \quad (7)$$

$$B_{sc} = \frac{1}{\delta} \cot \frac{\theta'}{2} \cdot \frac{\frac{1}{\delta} \tan \frac{\theta'}{2} - B'_{sc}}{\frac{1}{\delta} \cot \frac{\theta'}{2} - B'_{sc}}, \quad (8)$$

where

$$B'_{oc} = \tan \frac{\theta}{2} + B_{c2}, \quad (9)$$

$$B'_{oc} = -\cot \frac{\theta}{2} + B_{c2} + 2B_{c1}. \quad (10)$$

Consequently, the attenuation per unit section is given as follows with the following conditions of  $B_{oc}$  and  $B_{sc}$ :

$$\gamma = \begin{cases} 2 \tanh^{-1} \sqrt{\frac{B_{oc}}{B_{sc}}}, & 0 < \frac{B_{oc}}{B_{sc}} < 1 \\ 2 \coth^{-1} \sqrt{\frac{B_{oc}}{B_{sc}}}, & \frac{B_{oc}}{B_{sc}} \geq 1 \end{cases}. \quad (11)$$

Finally, the dimension of waffle type structure is determined based on attenuation of corrugated filter obtained by (11).

### III. SIMULATION OF WAFFLE TYPE WAVEGUIDE

We performed finite element method (FEM) simulation to confirm electromagnetic wave transmission in Ku-band. In simulation, we used COMSOL FEM simulation package. Simulation model is shown in Fig. 5. We determined the dimensions of rectangular structure as  $a = 12.96$  mm and  $b = 6.48$  mm in the model. As a result of simulation, for waffle type structure, we obtained  $l = 2.4$  mm,  $l' = 3.6$  mm and

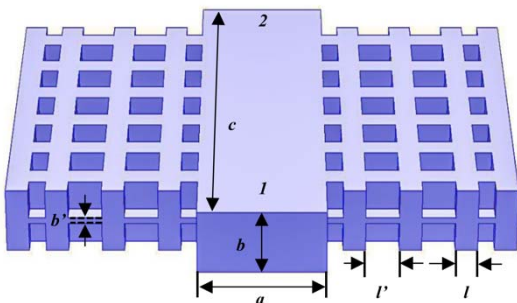


Fig. 5. Finite element method simulation model of the waffle type waveguide designed for Ku-band (12-24 GHz).

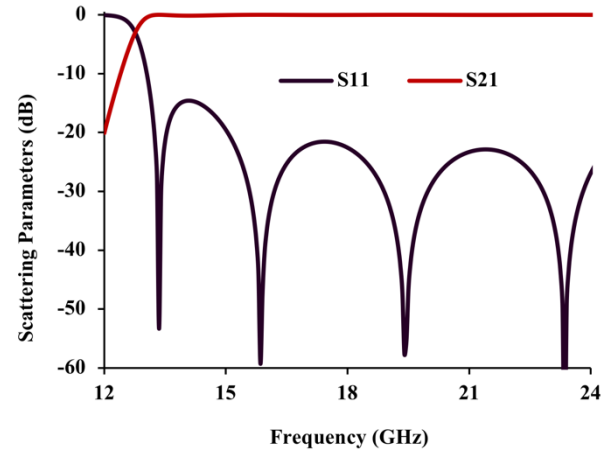


Fig. 6. Simulation result of scattering parameters for the waffle waveguide.

$b' = 0.48$  mm. We set the waveguide length  $c$  as 46 mm.

S-parameters simulation results are shown in Fig. 6. In the simulation, surface 1 and 2 in Fig. 5 were assigned as input and output port, respectively, and S-parameters were simulated at frequencies of 12 - 24 GHz.

In Fig. 6, transmission loss S21 was drastically changed at around 13 GHz and became below 0.05 dB at frequencies of 13.4 - 24.0 GHz. On the other hand, reflection loss S11 was lower than 20 dB at frequencies of 15.0 - 24.0 GHz. It means that designed waffle type waveguide is well operated at Ku-band. Moreover, by the electric field strength simulation, we could confirm that transmission characteristics of waffle type waveguide are similar to those of rectangular type usual waveguide, and clear attenuation in waffle type structure.

### IV. FABRICATION AND MEASUREMENT OF WAFFLE TYPE WAVEGUIDE

We fabricated waffle type waveguide with dimensions determined by FEM simulation. A photograph of fabricated waveguide is shown in Fig. 7, which was achieved by machining with Al. We fabricated upper and lower parts of the waffle type waveguide individually and combined together.

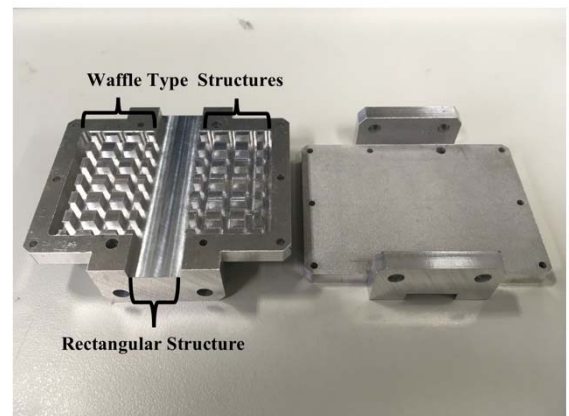


Fig. 7. A photograph of fabricated waffle type waveguide.

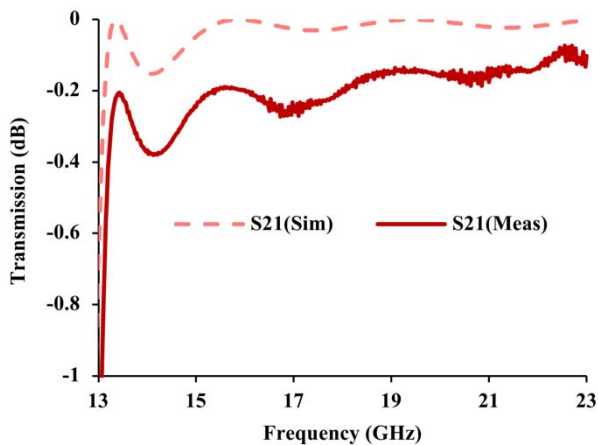


Fig. 8. Transmission loss (S21) measurement results (solid line). The simulation results (dashed line) are also shown for comparison.

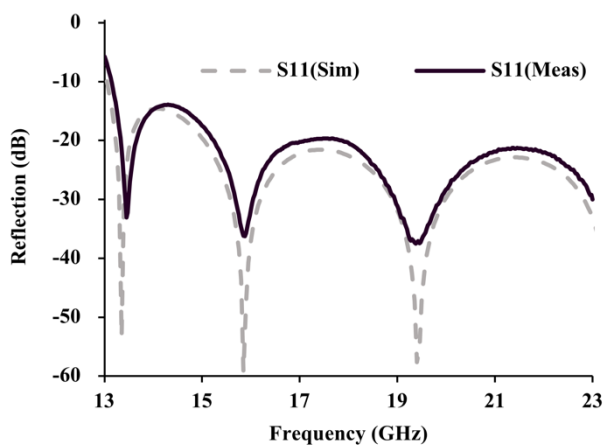


Fig. 9. Reflection loss (S11) measurement results (solid line). The simulation results (dashed line) are also shown for comparison.

S-parameter measurement was performed to verify operation of waffle type waveguide. Measurement results are shown in Fig. 8 and 9.

In Fig. 8, transmission loss (S21) is shown, which is compared with simulation results. They are well agreed and we achieved low transmission loss less than 0.4 dB over the frequency range. A little difference between simulation and measurement results causes from discrepancy of electrical conductivity of waveguide material. In simulation, we considered waveguide surface as a perfect conductor. However, real waffle type waveguide was made of Al with its own surface roughness. Furthermore, as shown in Fig. 9, we also achieved low reflection losses over the frequency range. Especially, frequency range showing reflection loss lower than 20 dB was from 15.2 GHz to 23.0 GHz, which corresponds to a 40.8% fractional band width. For the frequency range from

15.2 GHz to 23.0 GHz, the transmission losses become less than 0.3 dB. Moreover, reflection loss measurement results are well agreed to simulation ones.

## V. CONCLUSIONS

We fabricated and evaluated the waffle type waveguide for the first time.

The waffle type waveguide consists of rectangular structure and waffle type structure for electromagnetic wave transmission and attenuation, respectively. Bosses are periodically arrayed horizontally in waffle type structure and they are confronted vertically each other with air gap, which act as a low pass filter.

As a non-contact type waveguide, a waffle type waveguide was proposed to achieve less influenced waveguide from a machining accuracy and assembly accuracy [4]. However, it was only proposed by simulation study and not verified yet. Here, we proposed again the waffle type waveguide for Ku-band application. To verify its operation for the first time, we fabricated by machining with Al and performed S-parameter measurements.

As a result, the S-parameter measurement results well agreed with the simulation ones and we successfully verified the operation of the waffle type waveguide at Ku-band. We also achieved low transmission loss less than 0.3 dB and low reflection below 20 dB over wide frequency range from 15.2 GHz to 23.0 GHz which corresponds to a 40.8% fractional band width.

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## REFERENCES

- [1] D. Deslandes and K. Wu, "Integrated Microstrip and Rectangular Waveguide in Planar Form," *IEEE Microwave and Wireless Components Lett.*, vol. 11, pp. 68-70, 2001.
- [2] C. E. Collins, R. E. Miles, J. W. Digby, G. M. Parkhurst, R. D. Pollard, J. M. Chamberlain, D. P. Steenson, N. J. Cronin, S. R. Davies, and J. W. Bowen, "A New Micro-Machined Millimeter-Wave and Terahertz Snap-Together Rectangular Waveguide Technology," *IEEE Microwave and Guided Wave Lett.*, vol. 9, pp. 63-65, 1999.
- [3] F. Sammoura, Yu-Chuan Su, Ying Cai, Chen-Yu Chi, B. Elamaran, Liwei Lin, Jung-Chih Chiao, "Microfabricated Plastic 95-GHz Rectangular Waveguide," in *Proc. of IEEE International Conference on Micro Electro Mechanicals Systems 2005*, 2005, pp. 167-170.
- [4] O. Ishida, S.-O. Park, and Y. Tahara, "Grooved Waffle Waveguide Analysis and Its Application to THz Circuits Made of Noncontact Micromachined Halves," in *Technical Digest of 2005 International Symposium on Antennas and Propagation*, 2005, pp. 1157-1160.
- [5] G. Matthaei, L. Young, and E. M. T. Jones, *Microwaves filters, Impedance-Matching Networks, and Coupling Structures*, Norwood, MA, USA, Artech House Inc., pp. 380-409, 1980.