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FDTD Analysis on WPT Efficiency Between Circuit-Shape Leaky Waveguide and λ/2 Dipole Antenna for Snow Melting Application

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Abstract: The wireless transfer characteristics between a circuit-shape leaky waveguide and a λ/2 dipole antenna were analyzed with scattering parameters obtained with the FDTD method. The circuit-shaped leaky waveguide was composed of two pairs of straight slotted waveguides and two semicircular waveguides. The circuit-shape leaky waveguide was designed to achieve uniform electromagnetic field distribution with a source for snow melting with microwave radiations by microwave heating. The electromagnetic field of the circuit-shape leaky waveguide was firstly simulated with the FDTD method. Although the electromagnetic distribution exhibited the point symmetry with an off-set feeding point and a slot spacing $\boldsymbol{\lambda_g}$, it was nearly uniform. The wireless transfer efficiency and the maximum transfer efficiency for four locations at 2.45 GHz revealed that the farthest location from the feeding point had the largest WPT efficiency among four locations. This ensures the circuit-shape leaky waveguide's uniqueness. The circuit-shape leaky waveguide has favorable characteristics to provide WPT energy at any location above it.

Keywords: dipole antenna, leaky waveguide, wireless power transmission, WPT efficiency.

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1. INTRODUCTION

Efficient snow removal methods for heavy snowfall areas are in high demand, especially in depopulated and aging population areas. Snow melting systems using microwave heating have been proposed and investigated for snow removal [1],[2]. The proposed systems are expected to be low-cost, and require no storage areas for snow. In these systems, leaky waveguides, or slotted waveguides, are buried under the ground. Immediately above the waveguides are mortar blocks, heated by the microwave power leaking from the leaky waveguides like microwave ovens. The mortar blocks conduct the heat to the top surface on which piled-up snow is melted owing to the heat. As the radiating microwave power is generally the largest near the feeding point and gradually decreases is proportional to the distance from the feeding point, the mortar's temperature is unevenly distributed, which results in the difference in snow melting speed. Alternating feeding point layout using a left-handed waveguide with conventional right-handed waveguide was proposed to have the microwaves traveling in the same directions and to make the microwaves' electromagnetic field uniform [3]. In order to ease the snow-melting system deployment, the number of radiation power sources should be reduced. A circuit-shape leaky waveguide, in which microwaves travel along its circular shape, was proposed to effectively distribute the electromagnetic fields with a few microwave sources [4]. Reference [4] reported the basic characteristics of the circuit-shape leaky waveguide. The electromagnetic field distribution differed when the feeding point location and the distance between slots were changed. These relationships between the characteristics and feeding/propagation conditions still further need investigations. Besides the snow melting with microwave heating, we have also proposed utilizing the microwave as the electric power source wirelessly provided to a circulating trolly that runs on the circuit-shape waveguide. The trolly can be used to carry unmelted snow to the location where snow has already been melted. Wireless power transmission via the leaky waveguide is also useful to deliver electric power to automatic snow removal machines. In this paper, electromagnetic field distribution of the circuit-shape leaky waveguide with an offset feeding point was firstly analyzed by the FDTD method. Given the distribution, wireless power transfer (WPT) efficiencies between the leaky waveguide and a dipole antenna were then investigated with four different dipole antenna's locations. The dipole antenna was assumed to receive microwaves from which electric power was extracted for the trolly or snow removal machines. These efficiencies were calculated from the *S*-parameters obtained with the FDTD method. The WPT efficiency characteristics for the circuit-shape leaky waveguide were compared with those for a simple straight leaky waveguide [5].

2. FDTD SIMULATION FOR A CIRCUIT-SHAPE LEAKY WAVEGUIDE WITH OFFSET FEEDING POINT

In Figure 1, the structure of the proposed leaky waveguide with slot openings is illustrated. The slot openings are only at the straight part of the circuit-shape leaky waveguide. The frequency for the microwave heating was supposed to be 2.45 GHz, at which the free space wavelength λ_0 was 122.4 mm and wavelength in the waveguide λ_g was 147.4 mm, respectively. The length of the straight part, the inner radius of the semicircular part, and the outer radius of the semicircular part were 565 mm, 150 mm, and 260 mm, respectively. The waveguide's cross section was in line with WR-430. A feeding point can be set at any location in the circuit-shape waveguide. In Reference [3], the basic electromagnetic field characteristics were analyzed for the cases in which the feeding points were set at the middle of the straight part and the semicircular part, respectively. Unlike these conditions, the feeding point was set near a border between the straight and semicircular parts in this simulation. No investigations have been made with this condition before. The electromagnetic field characteristics generated by the microwaves leaking from the slot openings were numerically simulated with the FDTD method. The simulation used the high-performance computer system served by Information Initiative Center, Hokkaido University and the in-house large-scale electromagnetic field solver that was based on the standard FDTD method. Many program tunings and the parallelization were applied to enhance its processing performance. The FDTD problem space was discretized by 5.0-mm cubic cells. The convolutional perfectly matched layer (CPML) absorbing boundary condition with ten layers was implemented in the six outer boundaries of the problem space.

Figure 2 shows the simulated result. In this figure, the feeding point locates at upper left point, marked in a black dot. The maximum radiations were obtained near the feeding point and at the diagonal position to the feeding point. The electric field distribution shown in Figure 2 was almost symmetric with respect to the point, which agrees with the fact that the leaky waveguide's shape is symmetric. Specifically, it is interesting that the farthest location from the feeding point has also maximum performance in the electric field distribution. Although it seems that this is very simple fact, this is first time that the circuit-shape leaky waveguide is analyzed. The overall performance exhibited nearly uniform distribution. This distribution makes it suitable for use in the snow melting. Because the slot spacing size was λ_g, some grating lobes were generated especially inside of the circuit-shape. The grating lobes could be an issue for the communication systems, but has no negative impact for snow melting because the purpose of microwave transmission is to convey energy to melt snow.

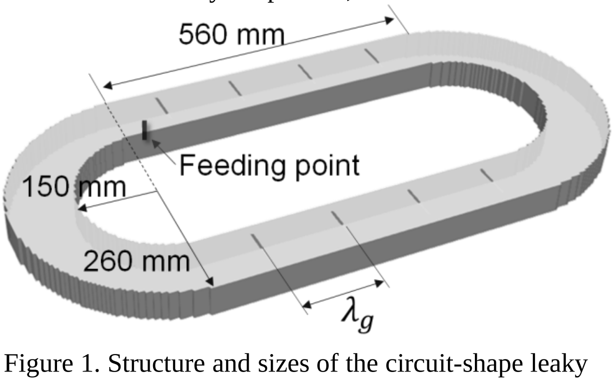

Figure 1. Structure and sizes of the circuit-shape leaky waveguide.

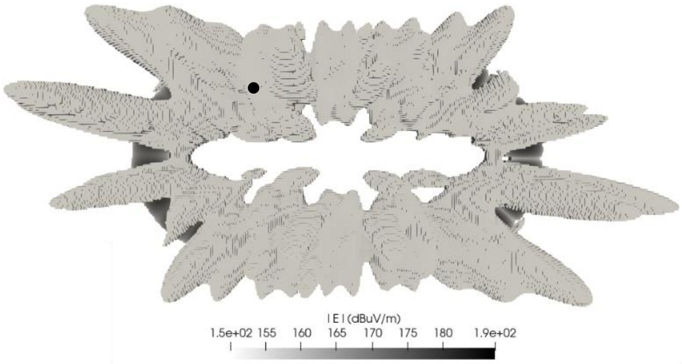

Figure 2. Electric field strength with off-set feeding point.

3. WPT EFFICIENCY ANALYSIS FOR FOUR SLOT LOCATIONS OF THE CIRCUIT-SHAPE LEAKY WAVEGIDE

3.1 *S*-parameter Simulation

The *S*-parameters between the leaky waveguide and a λ/2 dipole antenna were simulated with FDTD method to calculate its WPT efficiency (η) and maximum WPT efficiency (η_{max}). Four different slot locations were chosen for comparison, which were;

1. the straight-part waveguide in which the feeding point exists, and the nearest slot to the feeding point,
2. the straight-part waveguide in which the feeding point exists, but the furthest slot from the feeding point,
3. the opposite side of 1, without the feeding point,
4. the opposite side of 2, without the feeding point.

These locations with respect to the feeding point are shown in Figure 3. The dipole antenna's length was 55 mm, which was composed of 11 cells in the simulation structure data. Although the ideal $\lambda_0/2$ length at 2.45 GHz was 61.2 mm, the cell number for the dipole antenna should be odd number to have an excitation/termination point in the middle of the antenna due to simulation restrictions. The height from the waveguide's top surface to the dipole

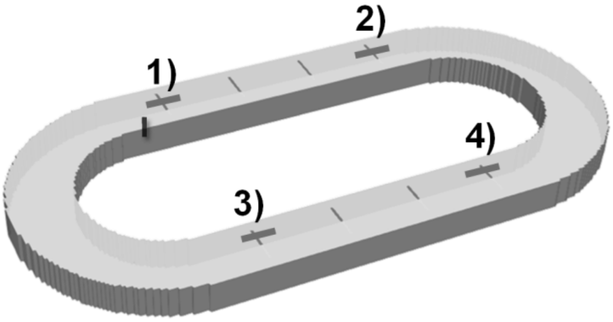

Figure 3. Locations where the dipole antenna was located.

antenna was 15 mm. The dipole antenna's performance was simulated with the same FDTD method beforehand, and the results matched with the numerical calculations.

Figures 4-7 shows the simulated *S*-parameters between the circuit-shape leaky waveguide and the λ/2 dipole antenna. The port 1 was set to the feeding point in the circuit-shape leaky waveguide, while the port 2 was set to the λ/2 dipole.

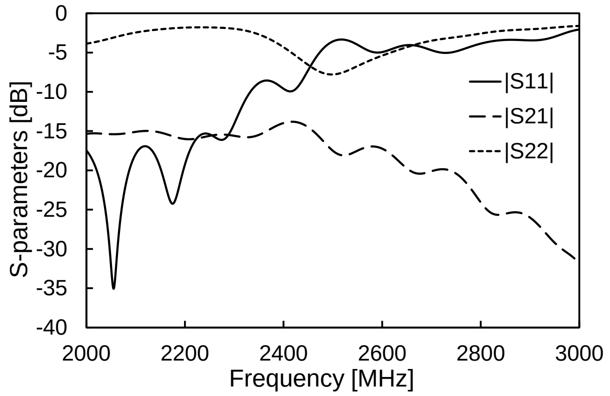

Figure 4. Simulated *S*-parameters for the location 1.

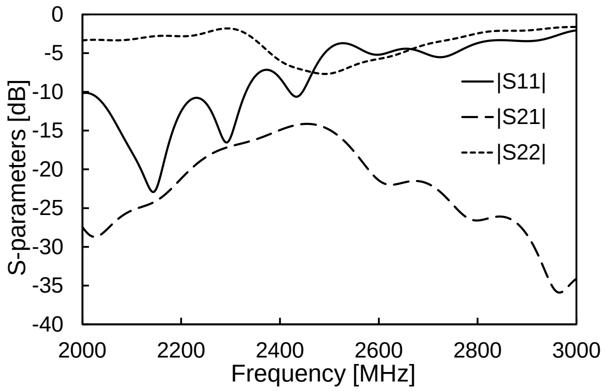

Figure 5. Simulated *S*-parameters for the location 2.

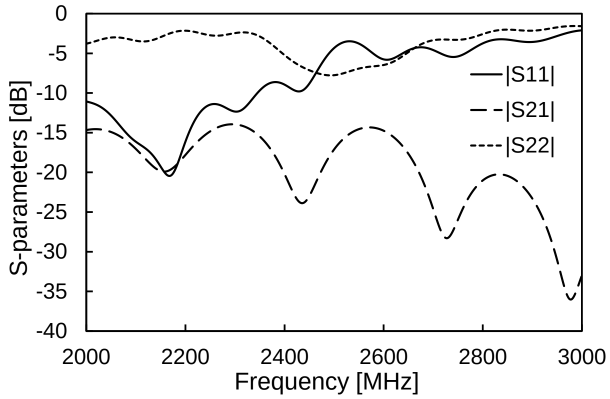

Figure 6. Simulated *S*-parameters for the location 3.

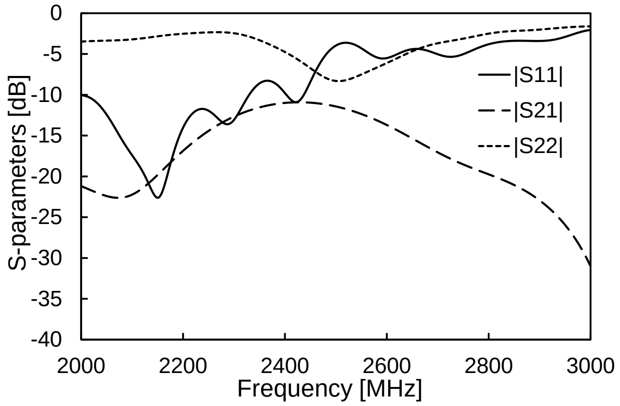

Figure 7. Simulated *S*-parameters for the location 4.

The simulated *S*-parameters for the dipole antenna location 1 are shown in Figure 4. Periodical dips could be observed for S_{11}. A dip in S_{22} was -7.8 dB at 2.498 GHz, and a maximum for S_{21} was -14.5 dB 2.450 GHz. In Figure5, which is for the location 2, periodical dips for S_{11}, a dip in S_{22} -7.7 dB at 2.491 GHz, and a maximum for S_{21} -14.1 dB at 2.454 GHz could be observed. In Figure6 for location 3, periodical dips for S_{11}, and in S_{22} -7.8 dB at 2.493 GHz, periodical dips for S_{21} could be seen. In Figure7 for location 4, periodical dips for S_{11}, a dip for S_{22} -8.3 dB at 2.505 GHz, and a maximum for S_{21} -10.9 dB at 2.428 GHz could be observed.

Regarding S_{11}'s in Figures 4-7, all of them exhibited periodic characteristics. Because a clockwise wave and a counterclockwise wave were excited at the feeding point at the same time, their merged amplitude could be enhanced or suppressed depending on their phase and amplitude conditions when they encountered. In addition, these conditions also depend on the frequency. These effects should contribute for generating the periodicity in S_{11}'s.

3.2 WPT Efficiency Analysis

From *S*-parameters simulated for 4 locations 1-4, η and η_{max} were calculated [6][7]. They are shown in Figure 8 for location 1, Figure9 for location 2, Figure 10 for location 3, and Figure 11 for location 4, respectively.

Looking at the η and η_{max} values at 2.45 GHz in Figures 8-11, they are 3.6 % and 5.6 % for location 1, 3.8 % and 5.4 % for location 2, 0.5 % and 0.7 % for location 3, and 8.5 % and 12.9 % for location 4, respectively. In previous work reported in [5], it was revealed that the straight leaky waveguide's WPT efficiency was the largest near the feeding point and eventually decreased as the distance from the feeding point increased. The circuit-shape leaky waveguide, however, has the largest WPT efficiency at the farthest location from the feeding point. This is the unique characteristics of the circuit-shape leaky waveguide found through this analysis. From S_{21} shown in Figures 4-6, some periodic performance was observed, but there was almost no periodicity in that shown in Figure 7. The frequency spacing between

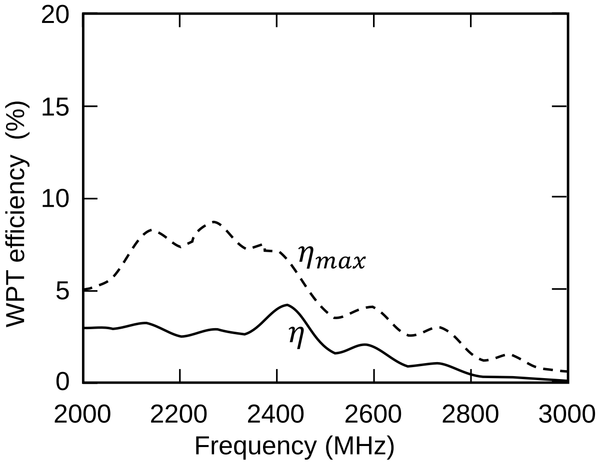

Figure 8. η and η_{max} for the location 1.

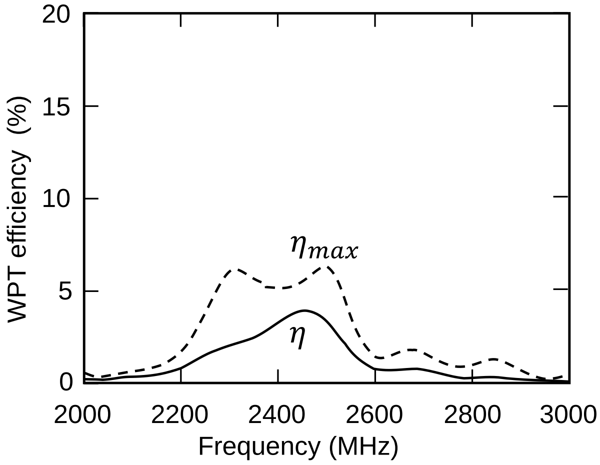

Figure 9. η and η_{max} for the location 2.

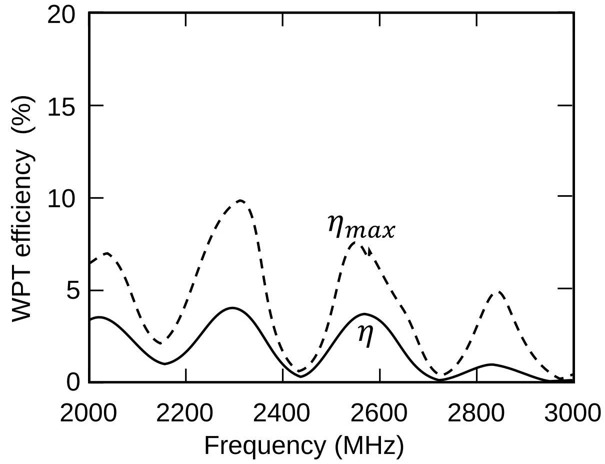

Figure 10. η and η_{max} for the location 3.

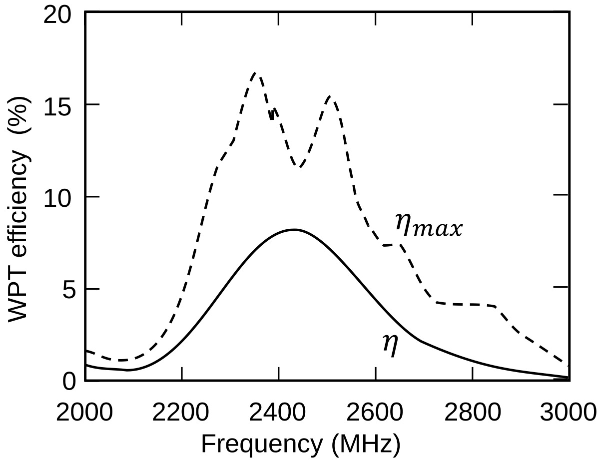

Figure 11. η and η_{max} for the location 4.

adjacent gaps in S_{21} depends on the traveling distance of the clockwise and counterclockwise waves, and the dip's depth is related to the amplitude's difference of two waves. When two amplitudes are the same, S_{21} goes to minus infinity. From these facts, the amplitude difference between the clockwise and counterclockwise waves should be large at the location 4. The reasons for this are presumably due to the location of feeding point, and layout between semicircular and straight waveguides, which needs further investigations.

The WPT efficiency at 2.45 GHz in Figure 10 was small. The two traveling waves cancelled out at the location 3 in this frequency. With optimizing the feeding point location and slot spacing, the WPT efficiency should be more uniform and improved than this analysis.

4. CONCLUSION

The electromagnetic distribution for the circuit-shape leaky waveguide with the offset feeding point was simulated with the FDTD method. Although the maximum directions appeared at near the feeding point and its diagonal directions, the overall performance was almost uniform. These properties made the circuit-shape waveguide suitable for microwave snow melting. The WPT and maximum WPT efficiencies were calculated from *S*-parameters obtained at 4 dipole antenna locations. It was revealed that the circuit-shape leaky waveguide had the largest WPT efficiency at the farthest location, i.e., location 4, from the feeding point, which was the unique characteristics of the circuit-shape leaky waveguide. The WPT efficiency at 2.45 GHz for location 3 was small. The clockwise and counterclockwise traveling waves excited at feeding point encountered and cancelled out at the location 3 in this frequency. In order to increase the WPT efficiency and to improve its uniformity, optimization of feeding point location and slot spacing should further be investigated.

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