Low Profile Cavity-Backed Slot Antennas for Microwave Energy Transmission

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1. Introduction

The Solar Power Satellite (SPS) [1] was proposed as a sustainable energy source for mankind in future. In the SPS system the solar power is converted into electricity and fed to microwave generators on the satellite. The microwave antenna (spacetenna) transmits the microwave power to a receiving antenna (rectenna) on the ground. The microwave energy is reconverted to electricity and then distributed to consumers. The most significant benefit of the SPS is the potential for large-scale clean energy systems to substitute the existing non-renewable energy sources. In Japan, the SPS2000 Task Team of ISAS Solar Power Satellite Working Group is involved in research to develop a solar power satellite system called the SPS2000 [2]. In the study the cavity-backed slot antenna is proposed as an element of the spacetenna of SPS2000. It is superior to other elements in mechanical strength and heat dissipation, and it can be made to have a low profile structure.

The authors have proposed the cavity-backed slot antenna geometry and its feeding structure that meets requirements of spacetenna and has a cavity height of one-tenth of a wavelength [3]. This paper investigates antenna design method of realizing a low profile element for the short-ended probe fed cavity-backed slot antenna. Moreover, we show the relation between the antenna parameters and the antenna characteristics. The design is carried out by employing the finite-difference time-domain (FDTD) technique [4]. Impedance matching at the frequency of 2.45 GHz is obtained by using appropriate probe location and slot width. The effectiveness of the design method is confirmed experimentally.

This paper is divided into four sections after this introduction. Section 2 describes the geometry of the cavity-backed slot antenna. Section 3 proposes antenna design method and shows antenna parameters that meet requirements of impedance matching. In Section 4 the design of a low profile cavity-backed slot antenna based on the approach is described then the experimental measurements and computed results are compared. The effectiveness of the design method is then discussed. Finally, a brief summary of this paper is provided in the last section.

2. Modeling of a cavity-backed slot antenna

Figure 1 shows the geometry and the dimensions of the antenna element investigated by the authors as an element of the SPS2000 spacetenna. The antenna polarization is linear and its bandwidth is not specified as a sinusoidal wave at the frequency of 2.45 GHz is used to transmit the microwave power. The dimensions of the element, d_x and d_y, are 75 mm (0.612 λ) and 90 mm (0.735 λ) where λ and h denote the wavelength related to the frequency of 2.45 GHz and the cavity height, respectively. To be suitable for mass production, the feeder geometry should be simple and be located on the bottom plane of the cavity. A feeder that meets these requirements and is best suited for the design of low profile structure is a short-ended probe terminated on the plane with the slot. P_f denotes the probe location measured from the center of the cavity bottom plane. l_s and w_s denote the slot length and its width, respectively. The long edge of slot is separated by S_f from the center of cavity top plane. When h = 12 mm, P_f = 0 mm, S_f = 24.5 mm, w_s = 3 mm and l_s = 63 mm, the return loss is more than 20 dB and the absolute gain is 7.2 dBi at 2.45 GHz [3]. We now propose a design method for realizing low profile antenna elements.

3. Design method for low-profile antenna elements

The antenna parameters that can be easily varied in the antenna structure are the probe location, the slot length and width. Figure 2 shows the computed input characteristics for several probe locations where S_f = 24 mm, l_s = 60 mm, w_s = 3 mm, the frequency range is from 2 to 3 GHz and circles denote the characteristics at 2.45 GHz. It is clear from the figure that the loci of the frequency characteristics on the Smith chart become smaller the larger the offset of the probe is. Therefore, the input resistance can be made to be 50 Ω by appropriately positioning the probe. On the other hand, the input reactance at the frequency of 2.45 GHz increases with increasing P_f. Next we should make the input reactance zero and realize impedance matching at the frequency of 2.45 GHz by tuning the slot parameters.

Figure 3 shows the computed input characteristics for several slot widths where l_s = 60 mm and $S_f + w_s$ = 27 mm. As the slot is widened, the input characteristics change. For the slot of more than 12 mm wide, the loci on the Smith chart are almost same for constant and the impedance point for 2.45 GHz move on the curve in the anti-clockwise direction. Therefore, enlarging the slot width can be used to decrease the input reactance introduced due to the large offset of the probe location. Especially, for the slot of more than 12 mm wide the input resistance is almost constant.

Figure 4 shows the computed input characteristics for several slot lengths where S_f =24 mm and w_s =3 mm. It is clear from the figure that the input reactance at the frequency of 2.45 GHz increases with increasing the slot length.

As a result of the above we propose the following methodologies for low profile cavity-backed slot antennas. First the probe location is shifted in the $-x$ direction until the curve of the frequency characteristics pass through the center of the Smith chart. Next the slot width, w_s, is enlarged until impedance matching is obtained at the frequency of 2.45 GHz. In the approach the slot length is kept constant when carrying out the procedure. If the initial width of the slot is more than 12 mm, expansion of the slot width is useful to adjust the matching frequency with the input resistance of 50Ω.

4. Design and performance evaluation of low-profile antenna elements

In the design methodology proposed in the previous section, antenna parameters are derived to realize impedance matching at 2.45 GHz. Figure 5 shows the different stages of impedance matching for the antenna with a height of 6 mm where the slot length, l_s, is 60 mm. The curve of the frequency characteristics passes through the center of the Smith chart when P_f = 24 mm. In this case the resonant frequency is much lower than 2.45 GHz. Extending the slot width from 18 mm to 21 mm realizes impedance matching at 2.45 GHz. Therefore, the optimum values of the probe location and the slot width are designed independently. Impedance matching is realized when the antenna parameters are P_f = 24 mm, l_s = 60 mm, and w_s = 21 mm.

Figures 6 and 7 show computed and measured input characteristics and radiation patterns for the parameters derived above. In these figures solid lines denote experimental results and circles denote computed results. It is evident from Figure 6 that the computed $|S_{11}|$ is less than –20 dB at the frequency of 2.45 GHz and agrees well with the experimental results. The absolute gain is 7.1 dBi at 2.45 GHz.

The design results for several cavity heights are summarized in Table 1. The antenna parameters shown in the table realize impedance matching at 2.45 GHz for a frequency bandwidth with a VSWR < 1.5. Figure 8 depicts the input bandwidths related to the cavity heights. It is evident from Table 1 and Figure 8 that a low profile antenna element requires a large offset of the probe location and has a narrow bandwidth.

5. Conclusion and summary

This paper proposes an effective design methodology of a low profile cavity-backed antenna element and gives an example of antenna parameters that realize impedance matching. The antenna element is to be used as an element of the microwave energy transmission system for the solar power satellite SPS2000. The design methodology is based on adjusting the probe location and the slot width in the short-ended probe fed cavity-backed slot antenna. The design method was used to derive antenna parameters that realize good impedance matching for element heights from 6 mm to 1 mm. Moreover, when the computed results are compared with experimental results, it is verified that the design method is effective and the derived antenna parameters are acceptable. The relations between the cavity height and the bandwidth were also discussed. It may be concluded that the design method is useful and accurate for impedance matching of the antenna element with arbitrary cavity height and also that valuable data for the development of the energy transmission antenna element of SPS2000 is shown.

References

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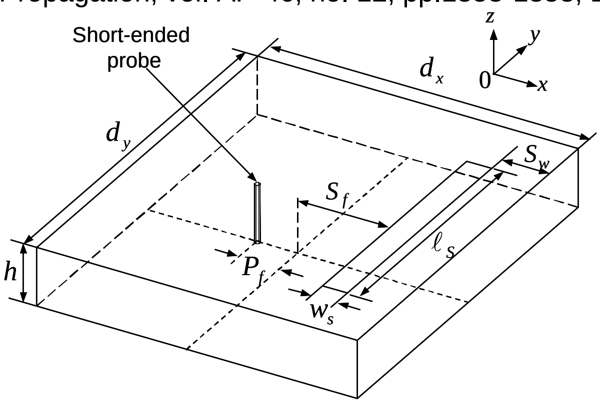

Figure 1. Geometry of a cavity-backed slot antenna fed by a short-ended probe.

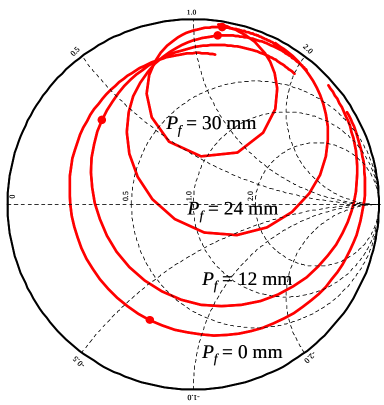

Figure 2. Computed input characteristics for different locations of the feeding probe with h=6 mm, l_s=60 mm, S_f=24 mm and w_s=3 mm in the 2-3 GHz frequency range. Circles denote the characteristics at the frequency of 2.45 GHz.

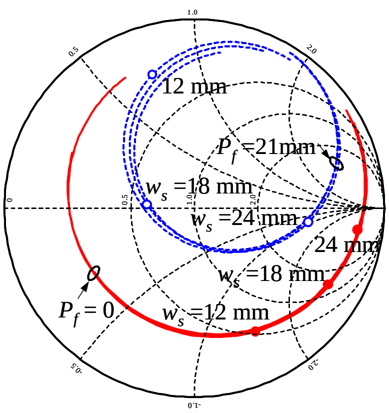

Figure 3. Computed input characteristics for different slot widths with h=6 mm, l_s=60 mm, $S_f + w_s$ =27 mm and w_s=3 mm in the 2-3 GHz frequency range. Circles denote the characteristics at the frequency of 2.45 GHz.

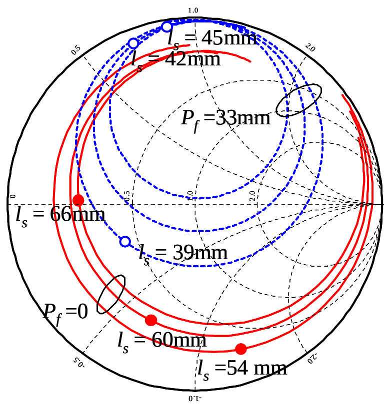

Figure 4. Computed input characteristics for different slot lengths with h=6 mm, S_f=24 mm and w_s=3 mm in the 2-3 GHz frequency range. Circles denote the characteristics at the frequency of 2.45 GHz.

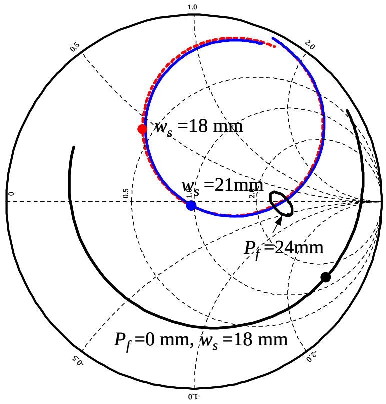

Figure 5. Design of the antenna element for the cavity height of 6 mm. S_f+w_s =27 mm, l_s =60 mm, the frequency is swept from 2 GHz to 3 GHz, and Circles denote the characteristics at the frequency of 2.45 GHz.

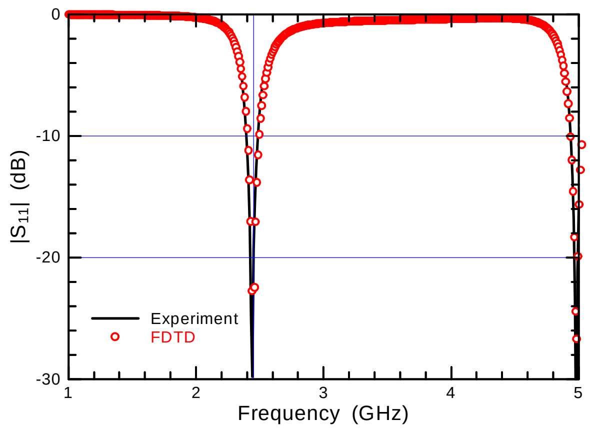

Figure 6. Input characteristics for h=60 mm, P_f =24 mm, l_s =60 mm, S_f+w_s =27 mm and w_s =21 mm.

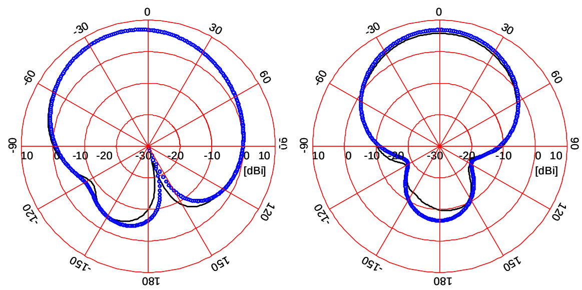

Figure 7. Radiation patterns in the E-plane (xz-plane) (a) and H-plane (yz-plane) (b) at the frequency of 2.45 GHz. Solid lines denote the experimental results and circles denote the computed results for h=6 mm, P_f =24 mm, l_s =60 mm, S_f+w_s =27 mm, and w_s =21 mm.

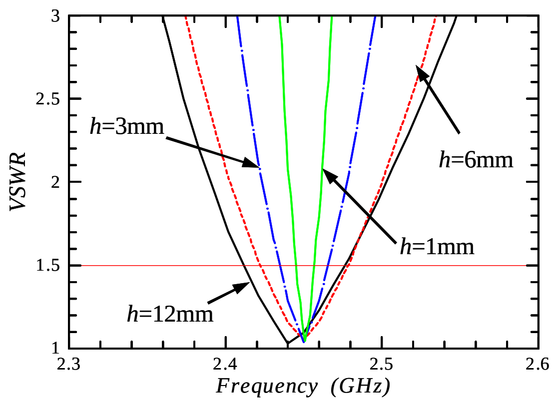

Figure 8. Computed bandwidth with respect to the cavity height.

Table 1. Computed bandwidth for different antenna parameters.

Cavity height h (mm)	12	6	3	1
Probe location P_f (mm)	0	24.0	28.5	29.5
Slot width w_s (mm)	3	21	22.5	21.6
Slot length l_s (mm)	63	60		
Bandwidth (MHz) (VSWR≤1.5)	65	56	30	11.5