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A Cavity-Backed Crossed-Slot Antenna Element for an S-Band Circular Polarization Spherical Coverage Satellite Antenna System

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Abstract

We present here the results of a preliminary study on a circularly polarized, S-band satellite antenna element consisting of a cavity-backed, crossed-slot radiating element and a microstrip feeding network. This study, involving extensive calculations and engineering model measurements, has verified the feasibility of the antenna element and will constitute the outset for the further development of the antenna system.

1. Introduction

A forthcoming mission within the Danish Small Satellite Programme [1], with the two-fold science objective of measuring oscillations in nearby stars and searching for gamma-ray bursts, calls for a circularly polarized, S-band telecommand/telemetry antenna system with a spherical coverage gain of -10dBi. The up- and down-link frequencies are fixed at a 241/220 ratio in the 2.0-2.3GHz frequency band, and the resulting 12% bandwidth thus allows for a single system. In order to fully exploit the avaiable space in the launch vehicle fairing and minimize the risk of mechanical damage, this antenna system must be flush-mounted with the solar panels covering the box-shaped satellite. The spherical coverage can be obtained by employing a space diversity principle with two hemispherical coverage antenna elements mounted on opposite faces of the satellite. Helix antennas [2] as well as turnstile antennas [3] have previously been employed for similar purposes but are disregarded here because of their protusion from the satellite body. We have instead chosen to employ a flush-mounted antenna element consisting of a cavity-backed, crossed-slot radiating element excited through a microstrip feeding network. This type of antenna element has mainly been used as aircraft antennas [4] due to their wide beamwidth and low profile. In the past decade mobile satellite services have motivated further developments [5, 6] and crossed-slot antennas have been introduced as radiating elements in phased array applications. The present paper reports the results of a preliminary study to verify the feasibility of this antenna element. The study, which involved extensive calculations with an integral equation-based computer code and impedance as well as radiation measurements on an engineering model, has shown that the cavity-backed crossed-slot antenna element offers good hemispherical radiation characteristics and a VSWR below 1.5 over at least a 12% bandwidth. The antenna suggested in this paper is similar to that of [5] but a larger bandwidth is obtained by using two wide slots.

2. Radiating element

The geometry of the cavity-backed, crossed-slot antenna is shown in Figure 1. The two slots are end-loaded to increase the effective length of the slot. The slots are backed by a square air-filled cavity which is approximately one tenth of a wavelength deep and the element is excited by four probes to obtain circular polarization and a rotationally symmetric radiation pattern. The probes 1-2-3-4 are sequentially phased $0°$-$90°$-$180°$-$270°$, penetrate the cavity from the back, and are connected to the top plate at 4 feed points. This feeding arrangement helps eliminating higher order modes and excites two orthogonal modes in phase quadrature resulting in left hand circularly polarized (LHCP) radiation. The resonance frequency, the antenna input impedance, and the impedance bandwidth are functions of several geometrical parameters. In particular, the resonance frequency decreases by increasing the width or the depth of the cavity, by increasing the probe displacement from the cavity center, by extending the length of

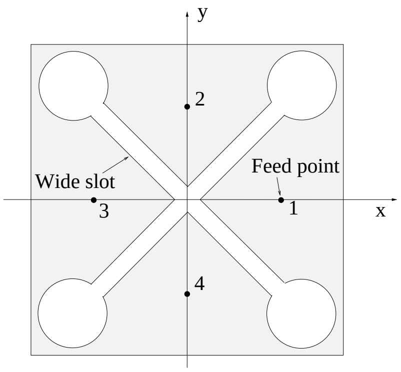


Figure 1: *Geometry of the crossed-slot radiating element with wide end-loaded slots and four feed points.*

the slot, by increasing the diameter of the endloadings, or by decreasing the slot width. The size of the ground plane surrounding the antenna, the thickness of the top plate, and the diameter of the probes also have non-negligible effects on the resonance frequency. An extensive parameter investigation has been performed by using the integral equation-based Method of Moments computer code IE3D$^{\text{TM}}$. At an early stage of this investigation an engineering model was fabricated to check the reliability of the theoretical results. The geometrical parameters in Table 1 were selected to arrive at an antenna impedance close to 50Ω, and the impedance measurements were performed on a HP8510 network analyzer. The input reflection coefficient for port 1 when fed by a 50Ω line is $\rho_1 = S_{11} - S_{13}$ due to the $0°$-$90°$-$180°$-$270°$ feeding of the probes that effectively decouples port 1 from port 2 and 4. A similar result holds for the other ports. The simulated and measured return losses are shown in Figure 2 where good agreement can be observed. The level of the return loss and the bandwidth are accurately predicted by the simulations with only a small deviation (2.4%) of the resonance frequency.

Geometrical parameters	
Cavity width	70.0 mm
Cavity depth	10.0 mm
Slot width	2.5 mm
Endloading diameter	12.0 mm
Top plate thickness	2.0 mm
Probe displacement	10.0 mm
Probe diameter	0.93 mm

Electrical characteristics	
Resonance frequency	2.15 GHz
Input impedance	$\approx 50\Omega$
Bandwidth (VSWR<1.5)	6 %

Table 1: *Geometrical parameters and simulated electrical characteristics of the engineering model.*

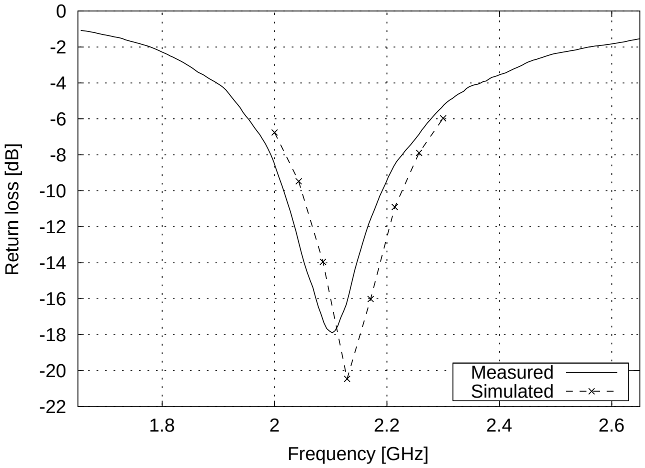


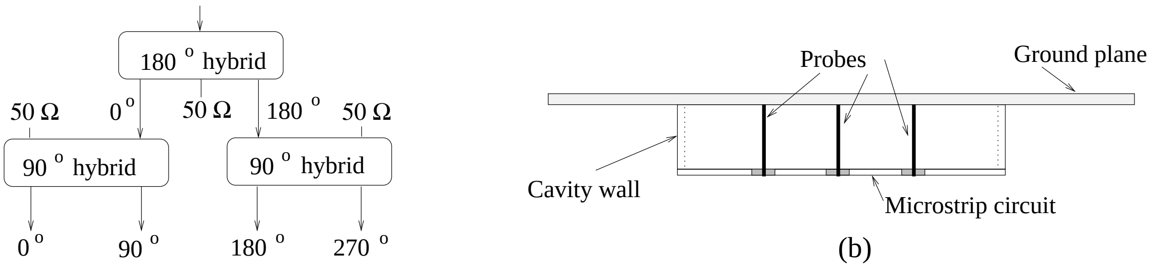
Figure 2: *Measured and simulated return loss of the engineering model mounted on a small square ground plane.*

From Figure 2 it is observed that the bandwidth of the engineering model radiating element alone is approximately 6% which is far from the 12% bandwidth specified for the antenna element combining the radiating element with the feeding network. However, further simulations have shown that the bandwidth can be doubled by changing the geometrical parameters listed in Table 1. This bandwidth meets the 12% specification and is considerably larger than the one obtained in [5], but the input resistance of each port at the resonance frequency is larger than the 50Ω of the engineering model.

3. Feeding network

The cavity-backed crossed-slot antenna element requires a phase-shifting power divider in order to provide the proper phases and impedance levels at the four probes. This is conveniently accomplished by using a microstrip feed network which incorporates a 180° hybrid and two 90° hybrids on a single substrate integrated into the back of the cavity. A block diagram of this circuit is shown in Figure 3(a).

Impedance transformers can be included, and the probes are fed directly through vias in the microstrip ground plane which also forms the back of the cavity. This arrangement allows the feed network to be added without increasing the overall size of the antenna, as depicted in Figure 3(b). An engineering model has been fabricated to measure the bandwidth and the phase errors of the feed network. These measurements show that the bandwidth is sufficiently large, and that the phase errors are kept below $\pm 5^\circ$ in the frequency band 2.0-2.3 GHz. Furthermore, the feed network was employed when performing radiation pattern measurements of the engineering model of the antenna, as described in Section 4 below.



(a)

(b)

Figure 3: *(a) Block diagram of microstrip feed network and (b), cross-section of antenna element showing the microstrip circuit integrated into the back of the cavity and the four probes fed through vias in the microstrip ground plane.*

4. Radiation pattern measurements

The computer simulations generally show that the radiation pattern of the crossed-slot antenna elements is practically unaffected by changes in the geometry of the radiating element. However, the radiation pattern is expected to be strongly influenced by the size and geometry of the ground plane since a non-zero vertical electric field component travels along the surface of the ground plane, diffracts at the edge, and creates an interference pattern with the directly radiated wave. This is not easily verified by IE3D^{TM} since the problem complexity increases rapidly with the size of the ground plane. Instead, preliminary radiation patterns of the cavity-backed crossed-slot antenna element mounted on a 400 mm diameter circular ground plane were measured at the DTU-ESA Spherical Near-Field Antenna Test Facility at the Technical University of Denmark. The radiation pattern of the antenna with the parameters of Table 1 was recorded at 2.15 GHz and is shown in Figure 4 for two different cuts. The desired LHCP field component exhibits a wide beamwidth and a high degree of rotational symmetry is observed by comparing the two cuts. The cross-polar RHCP component is quite weak. The direction of maximum radiation is in the broadside direction ($\theta = 0^\circ$) where the peak directivity is 7.5 dB. The direction of maximum radiation and the peak directivity is expected to change with the size of the ground plane. The favourable circular polarization properties observed in Figure 4 are also apparent in Figure 5. This figure shows the measured axial ratio in two different cuts and a 3 dB axial ratio beamwidth larger than 60° is obtained.

5. Conclusions and further work

A cavity-backed, crossed-slot, circularly polarized satellite antenna element has been investigated. Both simulated and measured results were obtained for an engineering model build in the first phase of the project and good agreement was observed. The simulations show that a bandwidth of 12% (VSWR$<$1.5) can be obtained. Furthermore, the integration of the antenna element and a microstrip feed circuit offers a flexible feeding principle without increasing the size of the antenna. The radiation pattern of the antenna is almost rotationally symmetric and a large circularly polarized beamwidth was observed. Thus, the antenna combines good radiation properties with a low-profile mechanically stable and flush-mounted design. The cavity-backed crossed-slot antenna elements are expected to be flush-mounted between the solar panels on the faces of the satellite and the presence of the satellite body may influence the radiation patterns considerably. A Method of Moments computer code capable of modeling the entire satellite body is under development to optimize the positions of the antenna elements and to ensure the desired coverage. Radiation measurements of the antenna elements positioned on a model of the satellite will be conducted to verify the theoretical results.

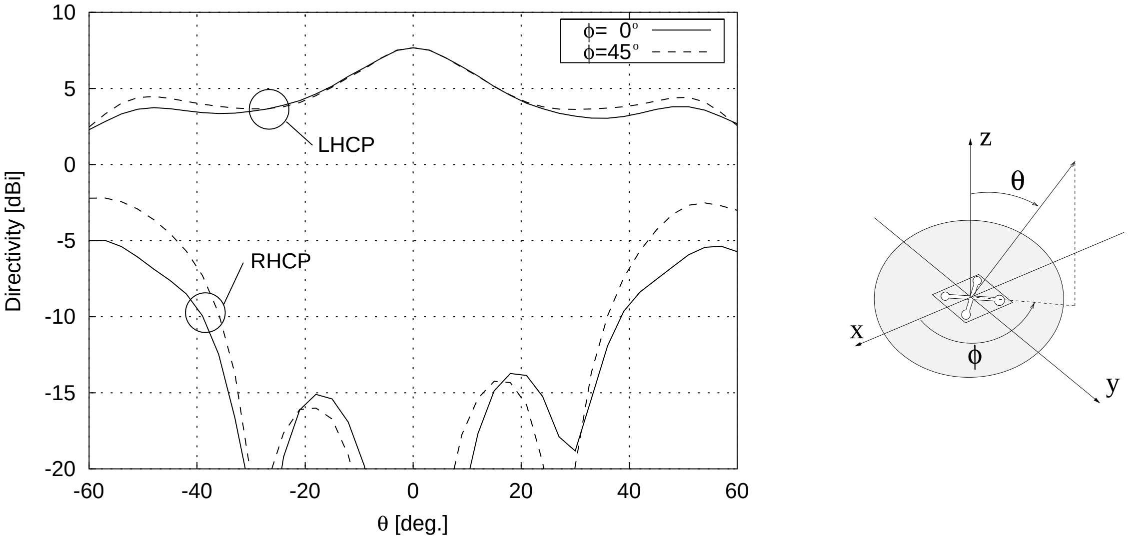


Figure 4: *Radiation pattern measured at 2.15 GHz of the engineering model mounted on a circular ground plane with a diameter of 400 mm (2.87λ). The LHCP and RHCP directivities are shown in the $\phi = 0^\circ$ and $\phi = 45^\circ$ planes.*

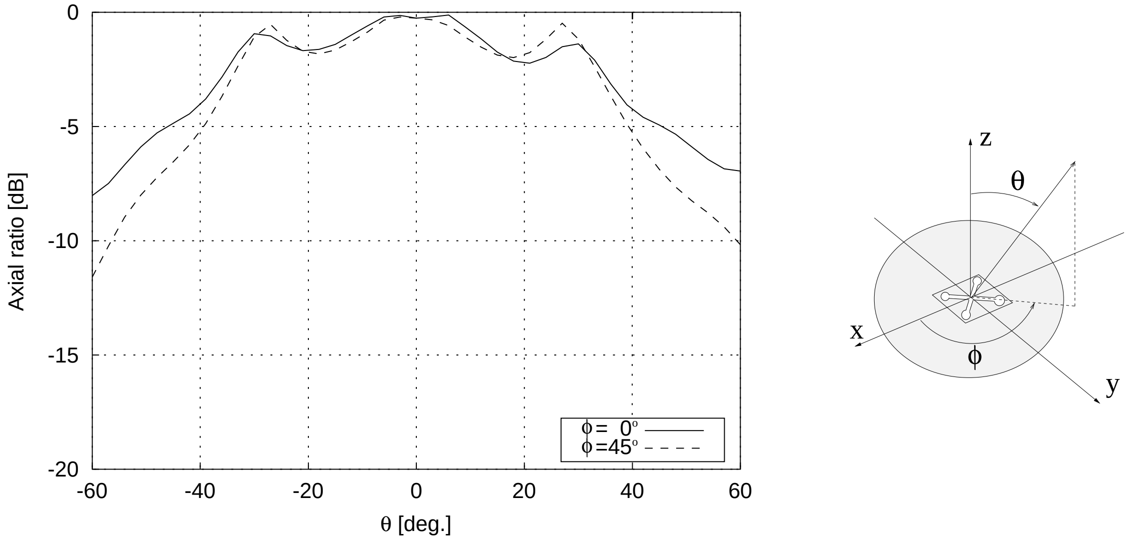


Figure 5: *Axial ratio measured at 2.15 GHz in the $\phi = 0^\circ$ and $\phi = 45^\circ$ planes.*

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