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Application of Slow Wave Structures for Miniaturized Satellite Feeding Networks

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Abstract

This paper describes the miniaturization of the NTNU test satellite (NUTS) UHF band feeding network. As the UHF band is easy to handle with commercial off-the-shelf (COTS) components and frequency allocation is affordable in ham radio bands, only proper feeding has to be achieved. A free space wavelength of roughly 70 cm is a challenge for plain microstrip components under CubeSat size constrains. Slow wave structures are used to reduce the length of microstrip lines in Wilkinson power dividers and supplemental phase shifters. The corresponding theory is outlined and employed for the two unit CubeSat NUTS. The proposed feeding network divides the input power from a radio subsystem equally into four parts and prepares phase differences to feed a turnstyle antenna circular polarized by short coax cable connections. It is inexpensive and easy to manufacture on a FR-4 printed circuit board (PCB) and can be applied to other substrates or radio bands where strict constrains on size and costs need to be enforced. The proposed design was fabricated and measured, showing good performance with respect to heavy miniaturization.

Introduction

The feeding network between the radio and the antenna of a CubeSat is a crucial part in the communication subsystem. It should achieve proper power split and accurate phase shifts between the radio output and different antenna terminals. The NTNU test satellite (NUTS) shall use a turnstyle antenna to realize circular polarized RF-emission with some directivity towards Earth. This has the advantage of a minimized polarization loss factor for the communication link and the disadvantage of a more complex feeding network in contrast to a simpler approach with linear polarized antennas. As radio links in the ham radio bands of 2 m and 70 cm are good to handle for COTS equipment of the ground station and the satellite, a proper feeding network design has to be developed. Space technology

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has heavy constraints on size and weight. Hence, a feeding network integrated into NUTS must have printed circuit board dimensions which do not exceed 9 cm x 9 cm to fit into the structure. This prohibits common microstrip (MS) feeding network design since a simple lambda-quarter transmission line has a length of around 9 cm on FR-4 substrate. Therefore, miniaturization approaches were evaluated.

To reduce the length of a transmission line or a whole power divider network, different techniques are found in literature. Among others, the following three strategies have been described: lumped element approaches where microstrip lines are replaced with capacitors and inductors to model the behavior of a transmission line as seen in [1] and [2], approaches based on transformers found in [3] and slow-wave based approaches reducing the phase velocity in transmission lines shown by [4], [5] and [6]. We decided to pursue a slow-wave based approach for the ease of manufacture (as the structure can be milled in-house) and only a minimum of lumped elements have to be soldered. Fewer soldered elements lead to better shake and shock resistance during launch.

As FR-4 substrate with a hight of 1.6 mm and metallization of 35 µm is used in the whole satellite, the feeding network should use the same as starting point, giving the possibility of easy mounting. Major drawback of FR-4 substrate is the uncertainty of electrical permittivity, inhomogeneities of the dielectric and a high loss tangent. It is believed that dielectric losses are low at the design frequency of 438 MHz. The uncertainty of electrical permittivity has heavy influence on the electrical length of transmission lines. To overcome this drawback measurements based on [7] were conducted. As a probe station was not available, SMA-connections were used to measure scattering parameters of the test-PCB. Hence, precision of the determination of the electrical permittivity is reduced. Nevertheless, a electrical permittivity $\epsilon_r = 4.8$ was approximated and is a good starting point for the feeding network design.

Feeding Network Design

To divide the input power of the feeding network into four equal output powers, a common Wilkinson Power Splitter (WPS)[8] was chosen as basis element. The three-port WPS in general allows equal power split with a good isolation of the two output ports. To achieve a four port equal split, two stages were taken into account, where the first stage WPS divides the power into two and is followed on each output port by a second stage WPS. The three power splitters introduce three lumped resistors. These are the only lumped elements inside the feeding network which need soldering. To reduce coax cable lengths a 180° phase shifter (PS) is integrated into one connection between the first stage WPS and one second stage WPS. Therefore only 0° and 90° coax cable connections to the antenna ports are needed. The described feeding network block diagram can be found in Figure 1.

As described already, common microstrip lines are too long to fit into a CubeSat. In [9] is a slow wave unit cell (UC) consisting of a Schiffman-section[10] and a open-circuited stub described. The structure is outlined in Figure 2. Basically, the Schiffman-section raises the inductance of the unit cell and the open-circuited stub adjusts, by increasing the capacitance,

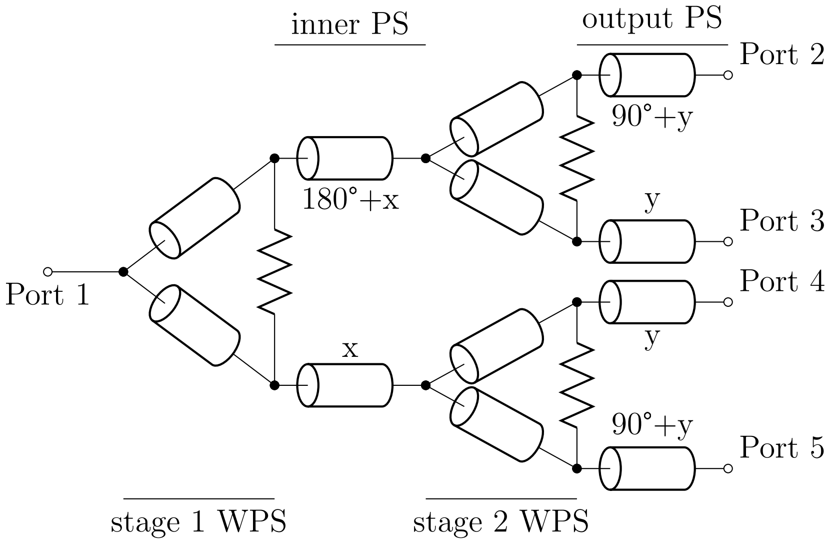

Figure 1: System block diagram with WPS and PS as elements. The variables x and y described the unknown electrical length for the direct connection between the stages and between output and antenna ports. The WPS and the inner PS are realized on the PCB and the output PS as coax cable connections.

the impedance of the unit cell. Recall the formula

$$Z_{uc} = \sqrt{\frac{L'}{C'}} \tag{1}$$

with distributed inductance L' and distributed capacitance C'. This results in reduced phase velocity and can easily be seen from transmission line theory:

$$v_p = \frac{1}{\sqrt{L'C'}}. \tag{2}$$

To judge the effect of the slow wave structure, the slow wave factor (SWF) ξ is a good parameter. ξ can be calculated by comparing the phase velocities of a common microstrip line and the unit cell structure, both having the same length in propagation direction.

$$\xi = \frac{v_{p,MS}}{v_{p,UC}} \tag{3}$$

The calculations of microstrip line properties were carried out with help of “wcalc”[1] and are based mainly on [11]. Unit cells for size reduction of $50\,\Omega$ and $70.71\,\Omega$ microstrip lines were calculated and results are presented in Table 1. It is advantageous that the lengths l_b and W mainly influence the unit cell impedance and the SWF, respectively.

These size reductions lead to increased attenuation resulting from the small width of the Schiffman-section and transition losses. Regarding the given the electrical lengths of a unit

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[1] `http://wcalc.sourceforge.net/`

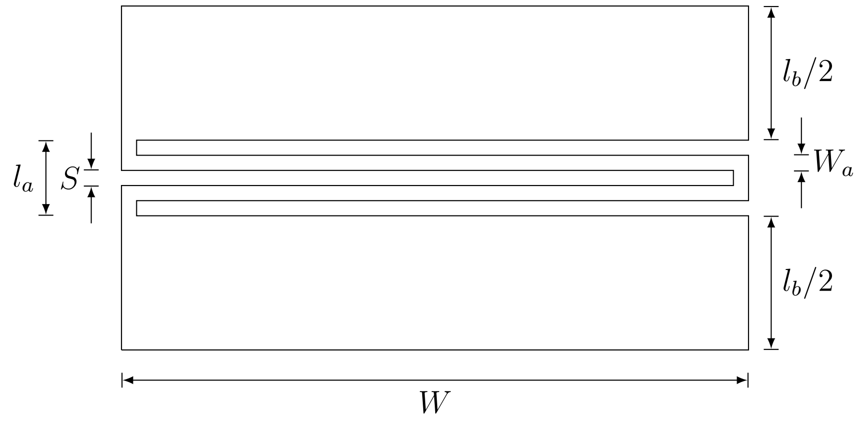

Figure 2: Unit cell consisting of a Schiffman-section and a open-circuited stub. Dimensions: l_a - length of the Schiffman-section, l_b - length of the low impedance line section, S - slot width between unit cell elements, W - width of the open-circuited stub, W_a - width of the Schiffman-section microstrip. Figure based on [9].

Table 1: Unit cell properties for $f = 438\,\mathrm{MHz}$ on PCB (FR-4 $h = 1.6\,\mathrm{mm}$, $\epsilon_r = 4.8$) with constant geometric parameters $S = 0.2\,\mathrm{mm}$ and $W_a = 0.2\,\mathrm{mm}$.

Parameter	WPS unit cell	PS unit cell
l_b	2.8 mm	11.5 mm
W	8.1 mm	8.8 mm
Z_{uc}	70.87 Ω	50.17 Ω
θ	16.8°	29.6°
ξ	6.2	2.6

cell the count for the 90° WPS and the 180° PS transmission line needed is five ($5 \times 16.8° = 84°$) and six ($6 \times 29.6° = 177.6°$), respectively. The residual phase shifts were achieved by common microstrip line connections between the the different unit cells. For linking SMA-connectors to the structure small tapered microstrip lines were designed. The whole PCB layout can be seen in Figure 3.

Results

The following measurements were conducted with a “Rohde and Schwarz ZNB8” vector network analyzer calibrated with a “Hewlett Packard 85052D” calibration kit. The reflection parameters on all ports are below $-15\,\mathrm{dB}$ in the 70 cm band. Nevertheless, the reflection at port one is minimal at about 390 MHz and therefore detuned from the design frequency (see Figure 4). The reflection parameters at the ports after the 180° PS are degraded at design frequency.

The transmission parameters remain quite constant in the desired frequency range and decline at frequencies higher than 450 MHz. The transmission to the output ports is more attenuated in the 180° PS due to high losses in the slow wave structure. As seen in Figure 5 the

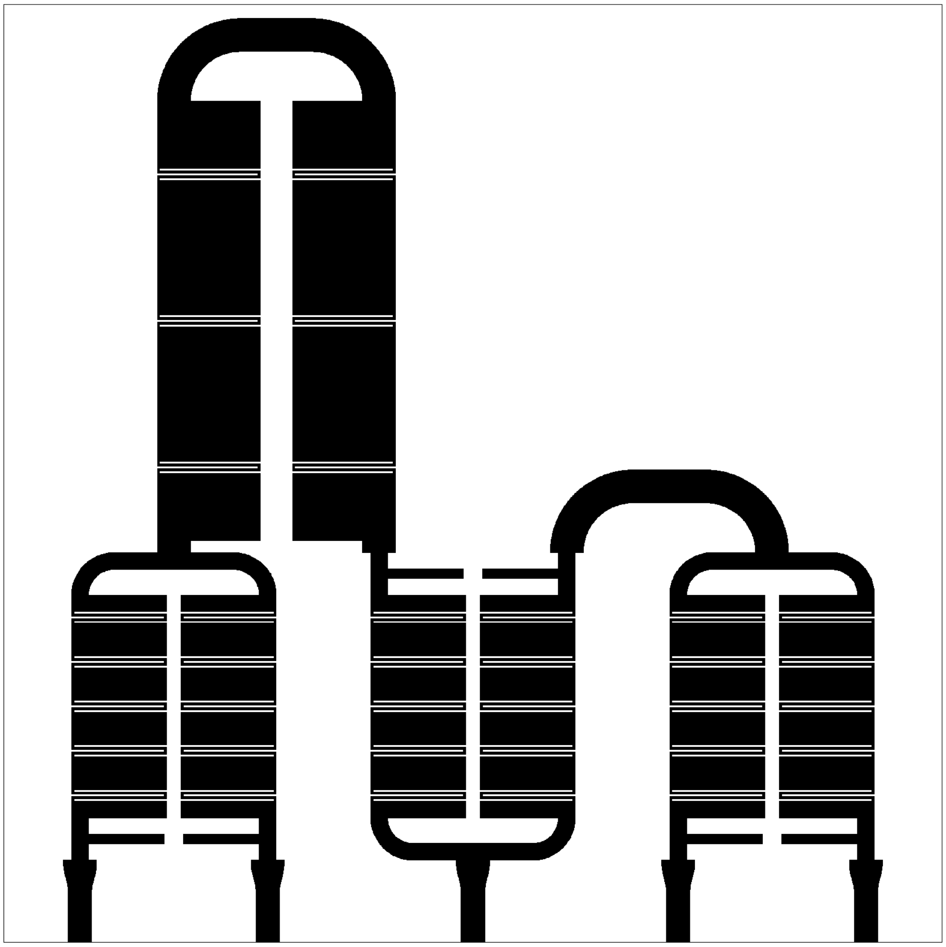

Figure 3: PCB layout of the proposed feeding network with tapered input port in the middle, followed by the first stage WPS. Branching from this are two stage connectors, one equipped with a 180° phase shifter, followed by the second stage WPSs and tapered output ports.

transmission to the outer output ports is slightly better. At design frequency the overall insertion loss is

$$IL = 1.5\,\text{dB} + 1.6\,\text{dB} + 0.7\,\text{dB} + 0.8\,\text{dB} = 4.6\,\text{dB}. \tag{4}$$

Minimum insertion loss of the prototyped network is at about 370 MHz. Hence, the transmission parameters show the same tendency as the reflection parameter at port one. Both are better at lower frequencies.

The isolation parameters between all ports are below $-15\,\text{dB}$. The WPS after the 180° PS isolates its outputs less than the other second stage WPS. This might be due to unequal termination at the inputs of the second stage WPSs. Isolation between two ports from different second stage WPSs is good and equal for all port combinations as seen in Figure 6.

The influence of the 180° phase shifter is shown in Figure 7. At design frequency the PS adds 196°. The design phase shift is already reached at 402 MHz.

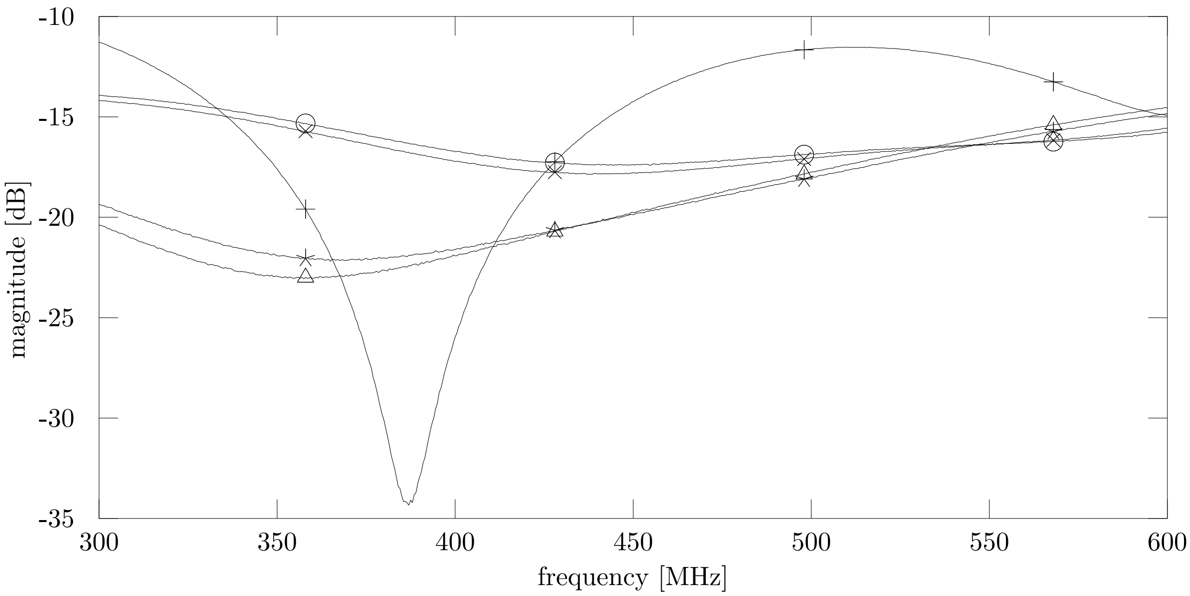

Figure 4: Reflection parameters of the slow wave feeding network. The parameters are denoted as "+" S_{11}, "×" S_{22}, "∘" S_{33}, "△" S_{44} and "⋆" S_{55}.

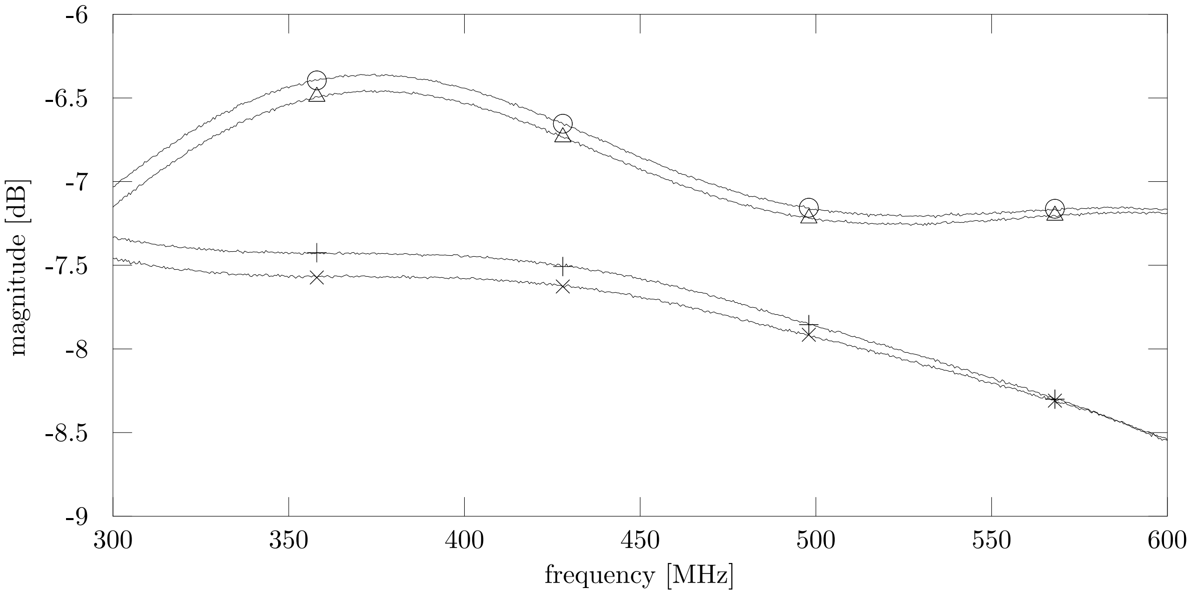

Figure 5: Transmission parameters of the slow wave feeding network. The parameters are denoted as "+" S_{21}, "×" S_{31}, "∘" S_{41} and "△" S_{51}.

Discussion

The feeding network was miniaturized to 8 cm × 8 cm with help of the calculated slow wave structures, and was fabricated as well as analyzed. The slow wave concept in general is suitable for CubeSat applications but needs further investigation to understand why the formulas given in [9] lead to a feeding network which has a better performance at frequencies below

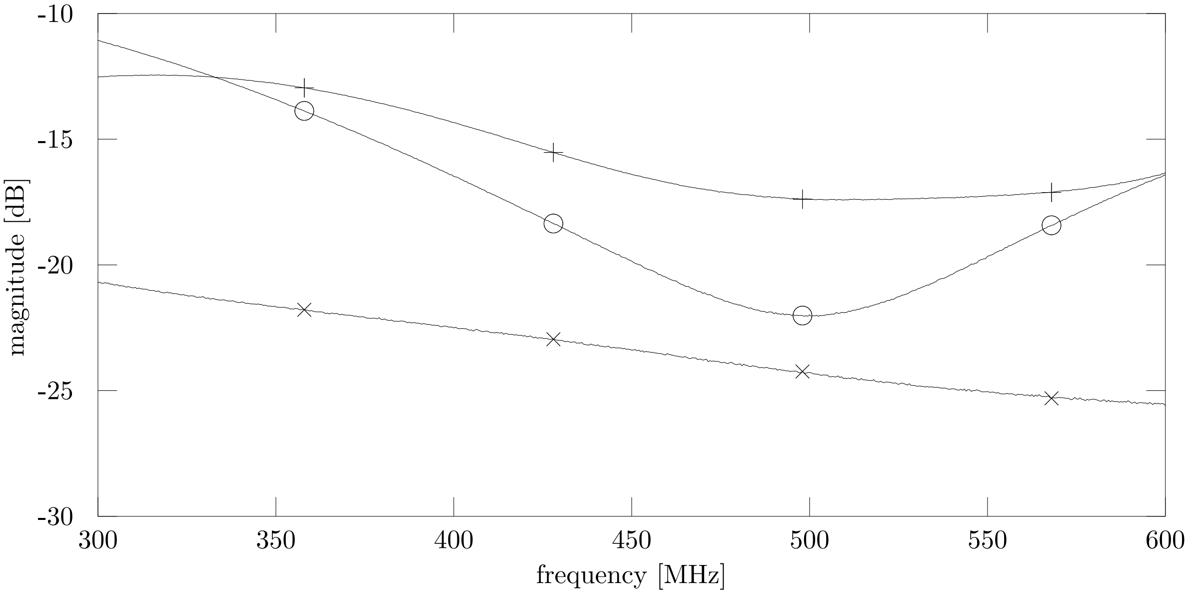

Figure 6: Isolation parameters of the slow wave feeding network. The parameters are denoted as "+" S_{32}, "×" S_{53} (S_{42},S_{52},S_{43}) and "○" S_{54}.

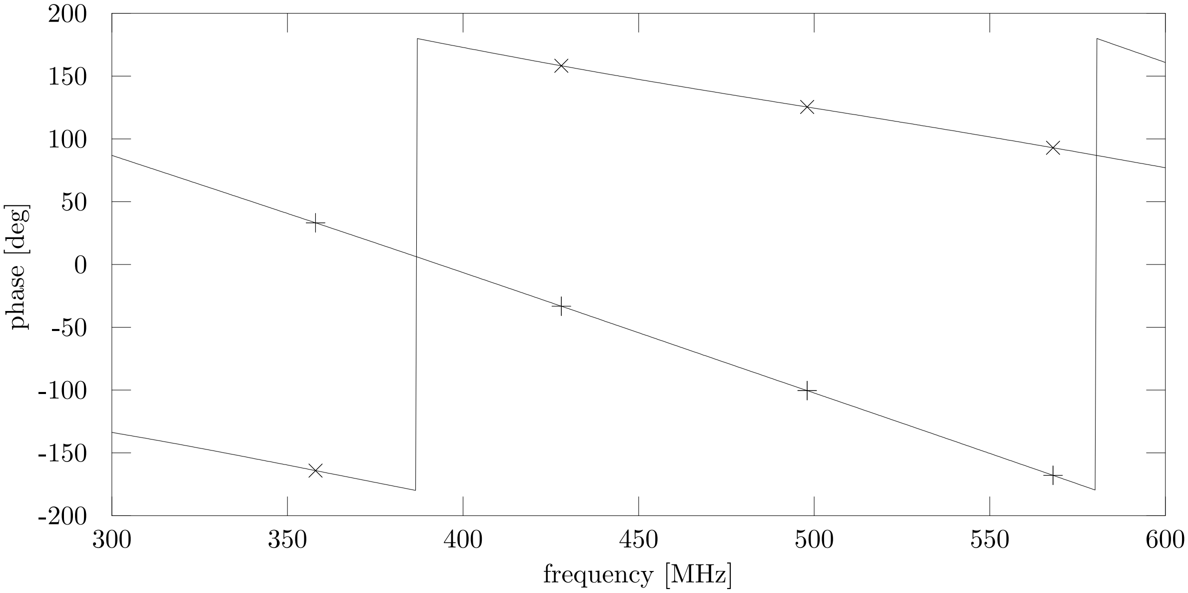

Figure 7: Phase of trasmission parameters of the slow wave feeding network. The parameters are denoted as "+" S_{21} (S_{31}) and "×" S_{41} (S_{51}).

the design frequency. Additionally, FR-4 as substrate is not recommended since the electric permittivity is uncertain and substrate losses are hard to calculate. Less insertion losses could be achieved in trade off bigger structures. Especially the width W_a of the Schiffman-section has heavy influence on the insertion loss of the whole network. As measured, the SWF of the calculated unit cells seems to be higher than assumed. This assumption is based on the stronger phase shift of the 180° PS at design frequency. The reason for this effect might be a greater electric permittivity or coupling between elements of the miniaturized structure.

The integration of the 180° PS should be re-evaluated as it adds nearly 2 dB insertion loss. If possible, COTS coax cables with the right length should be placed inside the satellite because it leads to less insertion loss in the feeding network.

If properly constructed, slow wave structures are useful in designing miniaturized feeding networks. Hence, more complex antennas can be used to improve the radio link between CubeSat satellites and ground stations.

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