A Novel Planar Antenna for CubeSats

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ABSTRACT

The UHF radio amateur band situated around 436 MHz is a very popular radio band for CubeSat Communications. This band has around 14.5 dB lower path loss compared to the popular S-band due to the lower frequency. The longer wavelength accompanied with the UHF band results in antennas that are relatively big compared to the size of a CubeSat. To communicate in this band, CubeSats are therefore equipped with linear wire antennas in dipole or turnstile configuration. Compared to patch antennas which are used to communicate in the S-band, these linear wire antennas have the downside that they need a deployment mechanism. This deployment mechanism increases the risk of failure during the mission, and subsequently asks more attention during design, integration and testing of the CubeSat. Furthermore, this system adds extra mass to the CubeSat and it takes up space that could be used by other subsystems. A novel planar antenna is proposed in this paper that obviates the need for deployment and meets most of the communication requirements for a CubeSat. Key characteristics of the proposed antenna is a gain of 3.72 dBi with a bandwidth of 2.82 MHz.

INTRODUCTION

For CubeSats, the amateur VHF and UHF radiofrequency bands are a popular choice to operate in. Because of the relatively large wavelengths that come with these frequencies, most CubeSat teams use an antenna system that is able to deploy large antenna elements once the satellite is put in orbit. This deployment mechanism adds extra mass, volume and complexity to the antenna system. The biggest risk for such a system is a deployment failure of the antennas. Although redundant deployment systems are usually in place to minimize the chance of a failure, the outcome of a failed deployment can result in a non-functioning communication system which makes the satellite useless.

A way to overcome this risk is the use of planar, or patch, antennas. Planar antennas are complete passive devices integrated in the cubesat body that do not need a deployment mechanism. Since the introduction of the CubeSat standard in the late 90s by the California Polytechnic State University, CubeSat teams have only used patch antennas to communicate in the S-band at frequencies of 2.4 GHz.[1] At this frequency the wavelength is short enough to fit half wavelength patches on a cubesat body. The reason that not all cubesat teams use these patch antennas is because the higher frequencies of the S-band are accompanied with a higher path loss. The path loss can be calculated with equation 1.[2] In this equation is L_s the path loss in decibel, c_0 the speed of light, f_0 the frequency of the electromagnetic waves and S the path length.

$$L_s = 20 \cdot log\left(\frac{c_0}{4\pi f_0 S}\right) \tag{1}$$

The difference in path loss between a 436 MHz signal and a 2.4 GHz signal is calculated in equation 2. From this high difference it is clear why some teams still prefer to use the UHF band over the S-band.

$$20 \cdot log\left(\frac{2.4\,GHz}{436\,MHz}\right) = 14.8145\,dB \tag{2}$$

From this situation comes the question whether it is possible to design a planar antenna that can be used at UHF frequencies that combines the lower isotropic path loss of the UHF band with the simplicity, low mass and small size of a patch antenna. Two patch antennas are found in literature that radiate at frequencies close to 436 MHz and are designed specifically for space applications. These patches use two distinct ways to reduce the physical dimensions. In Mathur et al., a classic λ/4 antenna is described which uses a substrate with a high dielectric constant to decrease its size.[3] The antenna which is elaborated in Kakoyiannis et al. employs a fractal antenna design to fit the antenna on a

CubeSat structure.[4] Satellites missions employing patch antennas operating at the UHF band could not be found in the literature

REQUIREMENTS

The design of a UHF patch antenna needs to fulfil the requirements that are currently in place for the antenna system of the Delfi CubeSats:[5]

- The frequencies for communicating with the satellite shall lie within the frequency bands allocated to the amateur satellite service.
- The Antenna System shall be able to radiate the downlink signal over the UHF frequencies.
- All UHF and VHF antenna connections and transmission lines on the satellite will have an impedance of 50 Ω.
- The polarization of the Antenna System shall be circular.
- A single antenna deployment failure should not cause loss of the link.

This list is extended with two requirements restricting the physical dimensions of the antenna:

- The size of the antenna shall not exceed the dimensions of a 3U CubeSat side panel (30 cm x 10 cm).

This requirement states that the antenna need to fit on a single plane of the CubeSat body, allowing no deployment mechanisms to enlarge the area.

- The antenna patch shall not stick out more than 4 mm from the CubeSat side.
- If placed on the side, the antenna shall not be wider than 8 cm.

If the patch is placed on the side, it has to be made sure that when the patch sticks out, the whole satellite still needs to fit in the launch POD. In figure 1 and 2 the available space for the patch is visible. The patch needs to have a width that is smaller than 8 cm. The patch may stick out 4 mm because a deployable solar panel needs to fit on top of the patch allowing the whole assembly to fit in the launch POD.[6]

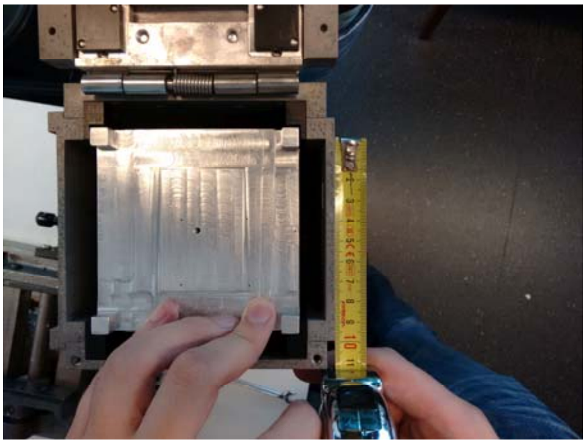

Figure 1: Dummy 3U CubeSat in a launch POD showing the space available for the patch to stick out. [Credit: Jan Verwilligen]

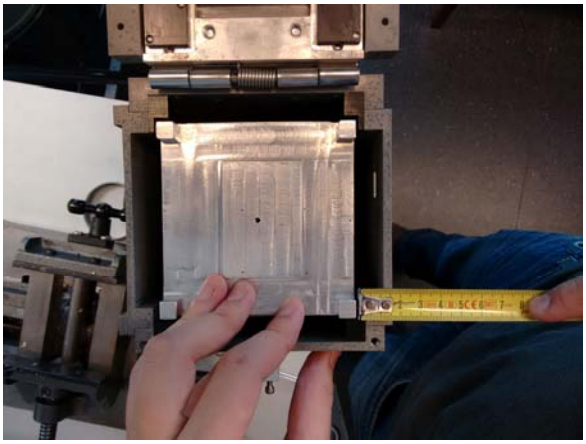

Figure 2: Dummy 3U CubeSat in a launch POD showing the space available for the patch to stick out. [Credit: Jan Verwilligen]

DESIGN

As was mentioned in the introduction, all CubeSat teams up till now use linear wire antennas to accomplish communication in the UHF band. The reason behind this is the relatively large wavelength of 70 cm that corresponds with this frequency. This rules out the usage of a half or quarter wavelength patch due to the limited area available on the CubeSat body.

A Planar Inverted F Antenna, or PIFA, can circumvent this limitation. A PIFA is a type of patch antenna where the patch is short circuited with a strip to the ground plane which allows the antenna to resonate at smaller antenna sizes compared to regular patch antennas.[7] An example of this type of antenna can be seen in figure 3. In this figure the X/U and Y/V direction are in the antenna ground plane where the Z/N direction is perpendicular to this plane. The dimensions that define the size of the antenna are L_1, which is the width of the antenna, L_2, which is the length of the antenna, H, which is the height of the antenna above the ground plane. The short circuit strip has a width W, with dss as the distance between the short circuit strip and the long edge of the antenna and df as the distance between the short circuit strip and the feed of the antenna. When this antenna is observed from the side, the patch, the short circuit strip, and the antenna feed form an F turned on its side.

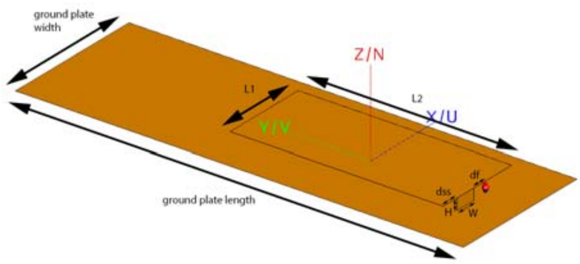

Figure 3: Structure of the PIFA.

The short circuit strip, or shortening strip, is the element in the antenna design that allows the size reduction of the PIFA compared to a regular rectangular patch antenna. In general the rule of thumb for sizing a PIFA antenna, as presented in Hirasawa et al., is given by equation 3.[8]

$$L_1 + L_2 + H - W = \frac{c_0}{4 f_0 \sqrt{\epsilon_r}} = \frac{\lambda}{4\sqrt{\epsilon_r}} \qquad (3)$$

In this equation, L_1 is the width of PIFA antenna, L_2 is the length of the PIFA antenna, H is the height of the patch, W is the width of the shortening strip, c_0 is the speed of light in vacuum, f_0 is the resonance frequency of the antenna and ε_r is the permittivity constant of the substrate between the ground plane and the PIFA patch and λ is the wavelength corresponding with f_0. When no substrate is used, the dielectric constant is that of vacuum, $\varepsilon_r = 1$. As visible from this equation, the sum of both sides of the PIFA needs to be approximately a quarter wavelength when no substrate is present which is a large reduction in size compared to the common quarter wavelength patch where each side needs to be a quarter of the wavelength.

Design 1: A 1U Ground Plane

The first attempt to model an antenna according to the description above tried to fit the antenna on the top/bottom panel of a CubeSat structure. Therefore a ground plane of 100 mm by 100 mm was chosen. With a shortening width of 15 mm, equation 3 estimated that the sum of L_1 and L_2 needed to be equal to 186.9 mm if no substrate ($\varepsilon_r = 1$) was used. To fit this on the top or bottom panel, L_1 and L_2 need to be both 93.4 mm. Equation 3 does not completely define the antenna design, therefore some of the parameters require an initial estimate. The substrate is left out for this iteration because a substrate is not a necessity to create a functioning patch antenna in a simulation tool. The antenna was modelled in Feko using a different mesh refinement for the patch, ground, and the short circuit strip. Feko, short for FEldberechnung für Körper mit beliebiger Oberfläche, is a software suite that is specialised in computational electromagnetics (CEM). In table 1, a summary of the design parameters is given.

Table 1: Design parameters of the first antenna design

Parameter	Symbol	Value
Frequency	f_0	436 MHz
Wavelength	λ	687.6 mm
Patch length	L_1	93.4 mm
Patch length	L_2	93.4 mm
Patch height	H	7 mm
Short circuit strip width	W	15 mm
Distance short circuit strip to adjacent edge	dss	0 mm
Distance feed to short circuit strip	df	5 mm
Ground plane size		100 mm x 100 mm
Substrate		none
Mesh size ground plane		λ/50
Mesh size patch		λ/100
Mesh size short circuit strip		λ/200

With this model, the S11 parameters are calculated for the frequencies ranging from 350 MHz to 700 MHz. Plotting these scattering parameters in a Smith chart, as depicted in figure 4, shows that for all frequencies the antenna has a short circuit. When the scattering parameters are plotted in a Cartesian coordinate system, it is visible that a minimum is present around 25 MHz above the intended resonance frequency. However this minimum return loss is not as low as the industry standard of -10 dB.

After several iterations with modifications to the size of the patch and shortening strip, and the location of the shortening strip and the antenna feed, no improvements are obtained regarding the return loss and the short circuit that is visible in the Smith chart. Therefore the idea to fit the antenna on a 1U CubeSat side is abandoned for the next design iteration.

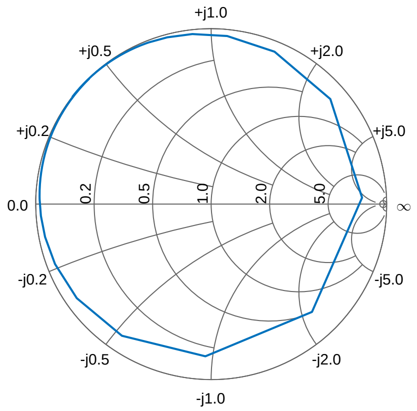

Figure 4: Smith chart with the complex S11 reflection coefficient of the first antenna design.

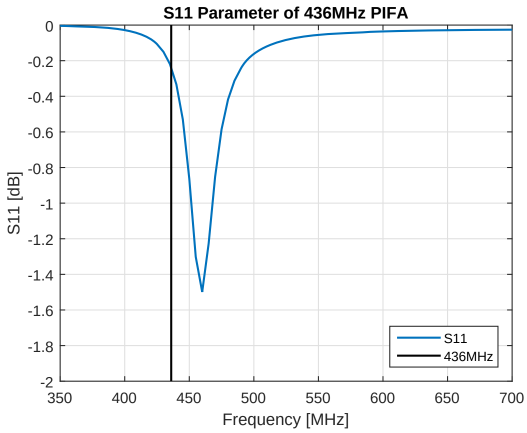

Figure 5: Reflection coefficient of the first antenna design.

Design 2: A 3U Ground Plane

In the second design, the chosen ground plane is the long side of a 3U CubeSat structure. Because of the space limitations in the launch POD, the length L_1 of the patch is set to be 60 mm. Since no substrate would be used yet for this design, the maximum height requirement of 4 mm is discarded since having the patch so close to the ground plate without substrate can influence the radiation properties. Therefore the height of the patch is set at 7.5 mm to isolate the patch from the ground plane. The short circuit strip width is kept at 15 mm and after optimizing the size of L_2, a return loss of -36 dB is obtained at a resonance frequency of 436 MHz. The values of the design parameters can be found in table 2. This return loss, as plotted in figure 6 is within the requirement to have a return loss of at least -10 dB. In the smith chart, presented in figure 7, it is visible that the complex return loss almost crosses the point [1,0] indicating an impedance match. This is also visible in figure 8 where the complex and real values of the impedance are plotted. The combination of the real and imaginary impedance result in a total impedance of 52 Ω at 436 MHz.

Table 2: Design parameters of the second antenna design

Parameter	Symbol	Value
Frequency	f_0	436 MHz
Wavelength	λ	687.6 mm
Patch length	L_1	60 mm
Patch length	L_2	142.7 mm
Patch height	H	7.5 mm
Short circuit strip width	W	15 mm
Distance short circuit strip to adjacent edge	*dss*	12 mm
Distance feed to short circuit strip	*df*	10 mm
Ground plane size		300 mm x 100 mm
Substrate		none
Mesh size ground plane		λ/50
Mesh size patch		λ/100
Mesh size short circuit strip		λ/200

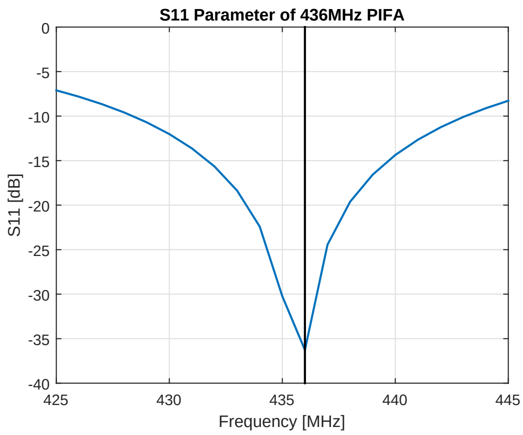

Figure 6: Return loss of the second antenna design.

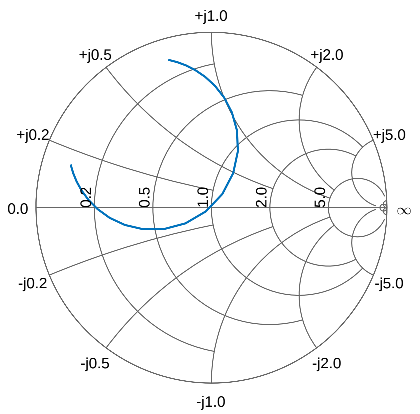

Figure 7: Smith chart plotting the complex return loss of the second antenna design.

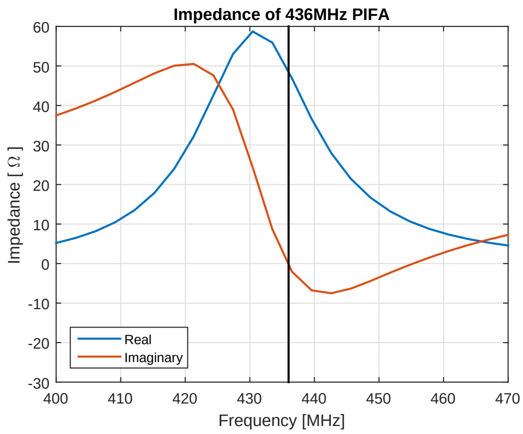

Figure 8: Impedance plot of the second antenna design.

Design 3: Adding the Substrate

Since the design presented in the previous section shows satisfying results regarding the return loss, this design can be expanded by adding a substrate between the patch and the ground plane, and by reducing the height of the patch above the ground plane. When adding a substrate to the design, a suitable medium has to be chosen with the right dielectric properties. When evaluating the S11 return loss plot in figure 6, it can be noted that the -10 dB bandwidth of the antenna is very narrow. The higher the dielectric constant of the chosen media, the narrower this bandwidth will become.[9] This leads to use Rogers RT/duroid®5880 as substrate between the antenna and the ground. This material has a dielectric constant of only 2.2.[10] The height of the patch is set to 3 mm.

When a substrate is used that has a dielectric constant that is higher than 1, the whole patch scales according to equation 3 with the square root of the constant ε_r. For a dielectric constant of 2.2, the sum of the antenna dimensions needs to be around λ/6 according to equation 4.

$$L_1 + L_2 + H - W = \frac{\lambda}{4\sqrt{2.2}} = \frac{\lambda}{5.93} \tag{4}$$

Resizing the antenna does not result directly in an antenna with a reflection coefficient below -10 dB and with the minimum at 436 MHz. The impedance matching of the antenna is more sensitive than the previous design. Not only the length L_2 has to be changed with a precision of 0.01 mm, also the position and size of the short circuit strip had to be changed with small steps as well as the distance between the short circuit strip and the antenna feed. After some tuning, the complex S11 goes close enough through the [1,0] point on the smith chart as can be seen in figure 9. The impedance of the antenna, as visible in figure 10, has its real maximum at 436 MHz and has an imaginary impedance close to zero at this frequency resulting in a total impedance of 52.9 **Ω**. The reflection coefficient, as plotted in figure 11, has a minimum value of -30 dB at the centre frequency of 436 MHz.

Table 3: Design Parameters of the third antenna design.

Parameter	Symbol	Value
Frequency	f_0	436 MHz
Wavelength	λ	687.6 mm
Patch length	L_1	40.45 mm
Patch length	L_2	104.84 mm
Patch height	H	3 mm
Short circuit strip width	W	11.46 mm
Distance short circuit strip to adjacent edge	dss	18.20 mm
Distance feed to short circuit strip	df	3.76 mm
Ground plane size		300 mm x 100 mm
Substrate dielectric constant	ε_r	2.2
Mesh size ground plane		λ/50
Mesh size patch		λ/100
Mesh size short circuit strip		λ/200

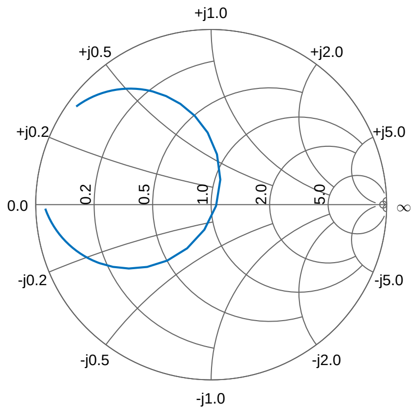

Figure 9: Smith chart of the complex reflection coefficient of the PIFA antenna.

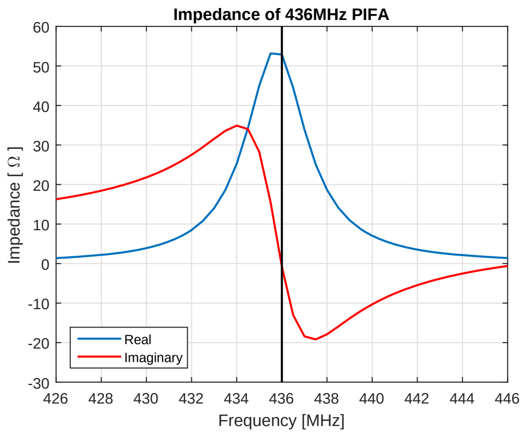

Figure 10: Real and imaginary impedance of the PIFA antenna.

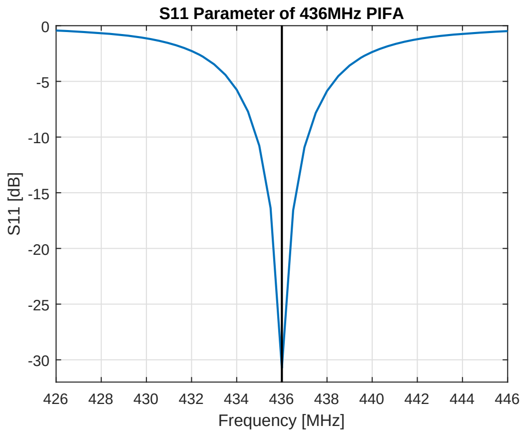

Figure 11: Reflection coefficient of the PIFA antenna.

RESULTS

Radiation pattern

The far field radiation pattern of the antenna is visible in figure 12 The maximum gain value is slightly lower than what is obtained with a conventional half-wavelength dipole antenna and the directivity is similar to the dipole antenna.[8] This gain (G) is linear polarized gain, which is the same gain as obtained with a dipole antenna. In figure 13 a polar plot of the XZ-plane and YZ-plane is visible. In this figure can be seen that the gain ranges in the XZ-plane from 1.66 dBi to 3.72 dBi and in the XY-plane from -9.98 dBi to 3.72 dBi. The Left Hand Circular and Right Hand Circular components of these gain have values that are consistently 3 dB lower than the linear counterparts.

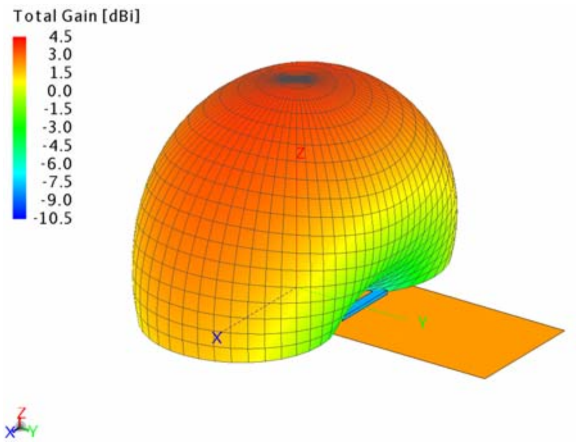

Figure 12: Far field radiation pattern of the PIFA at its resonance frequency.

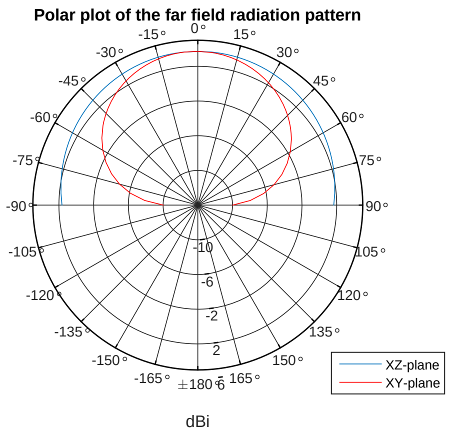

Figure 13: Polar plot of the far field radiation pattern of the PIFA at its resonance frequency.

Bandwidth

The bandwidth of an antenna is defined as `The range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard.[11] This specified standard is defined in most practical applications as a return loss that is smaller than -10 dB in the reflection coefficient. This corresponds to a voltage standing wave ratio (VSWR) of 2:1. The bandwidth for the antenna is with this definition 2.275 MHz. Relative to the centre frequency of 436 MHz, this corresponds to a fractional bandwidth (FBW) of 0.52 %.

When a return loss of -15 dB is considered, which relates to a VSWR of 1.5:1, the bandwidth is 1.26 MHz. This corresponds to fractional bandwidth of 0.29 %.

Electrical Size

The electrical size of the antenna, indicated with the symbol *ka*, is a way to compare the size of an antenna relative to the frequency at which it is operating. This is done by dividing the radius of the smallest sphere that can contain the antenna by a radianlength. The electrical size is thus a length relative to 1 radianlength or 1 rad. A radian length is defined as:[12]

$$1\,rad = \frac{\lambda}{2\pi} \tag{5}$$

In this equation is λ the wavelength. The smallest sphere which can contain the antenna can be calculated with equation 6:

$$R_{antenna} = \sqrt{\left(\frac{Depth}{2}\right)^2 + \left(\frac{Width}{2}\right)^2} \tag{6}$$

Which results for the antenna in:

$$R_{antenna} = \sqrt{\left(\frac{104.84\,mm}{2}\right)^2 + \left(\frac{40.45\,mm}{2}\right)^2} \tag{7}$$
$$R_{antenna} = 56.19\,mm$$

With this radius known, the electrical size, *ka*, of the antenna can be calculated with equation 8:

$$ka = 2\pi \frac{R_{antenna}}{\lambda} \tag{8}$$

Which results for the antenna radius and frequency in:

$$ka = 2\pi \frac{56.19\,mm}{687.60\,mm} = 0.51\,rad \tag{9}$$

Comparison to Other Planar UHF Antennas

In Kakoyiannis et al., a study is made of the performance parameters of planar antennas for small spacecraft.[4] Two of these antennas operate at the same low frequencies as the antenna discussed in this work. In table 4, the performance parameters of these two antennas are compared to the antenna presented in this work. From this table can be seen that the PIFA outperforms both antennas in 2 of 3 performance criteria. Only the bandwidth in the PIFA is smaller than the bandwidth of the antenna discussed in Mathur et al.[3]

Table 4: **Comparison of planar UHF microsat antennas.**

Antenna	f_0 (MHz)	FBW (%)	G_{max} (dBi)	ka (rad)
Mathur et al., 2001[3]	450	1.6	n/a	0.71
Kakoyiannis et al., 2011[4]	437	0.5	0.7	0.59
This work	436	0.52	3.72	0.51

Conclusion and Recommendations

In this technical note the preliminary design process was described of a 436 MHz planar antenna. The planar inverted F antenna that was created has a simulated return loss of -30 dB with a linear polarized gain of 3.72 dBi, a -10 dB bandwidth of 2.28 MHz and an electrical size of 0.51 rad. These performance parameters are in line with the deployable dipole antennas that are commonly used by CubeSat developers.

Comparing this antenna to the regular whip antenna systems such as the AntS developed by ISIS, the main benefit of this antenna is the absence of a deployment mechanism. This greatly increases the reliability of the antenna. This increased reliability reduces the time to test and verify the antenna which makes the antenna cheaper in usage. Because the antenna needs to be mounted on the CubeSat body, volume is freed within the CubeSat structure allowing other subsystems to be bigger. Due to the low profile of only 3 mm, enough space is available in de launch POD to fit a deployable solar panel on top of the antenna. The absence of electronics necessary to command the deployment system makes that the PIFA also has a lower power consumption than the antenna system with deployable antenna elements. The benefit of this antenna compared to a patch antenna operating in the S-band is the 14 dB of extra margin in the link budget for using UHF frequencies over S-band frequencies.

The drawback of this antenna is the small bandwidth. Not all CubeSats operating in the amateur UHF band use 436 MHz as centre frequency. Therefore, when a different frequency in the 432 MHz to 438 MHz amateur band is used, an optimization of the antenna dimensions is required. Comparing this to the AntS, where tuning is done by shortening the antenna element until the right resonance frequency is obtained, this frequency dependency makes mass producing the PIFA antenna more challenging.

For further development of this antenna type a few recommendations are in place:

A design iteration is required to prepare the antenna for manufacturing. This iteration should contain the following improvements:

- The substrate height should be increased from 3 mm to 3.175 mm which is a standard thickness for the RT/duroid® 5880 and will therefore simplify the manufacturing process.
- The short circuit strip should be replaced with a series of via holes to electrically connect the patch with the ground plane.
- The feed should be replaced with a construction that is more representative for a coaxial feed.

It has to be investigated how thermal expansion affects the radiation properties of the antenna.

Approaches to obtain circular polarization with the antenna was not included in this study. Several techniques such as dual feed systems and trimmed corners as described in Balanis et al. could be used but need some further research.[11]

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