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Impact of the Ground Plane Topology on the Performances of a Pyramidal Multiband Quadri-Element Antenna

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Abstract— This paper presents investigations performed on the ground plane topology of a pyramidal multiband quadri-element antenna recently introduced mainly for radio navigation applications. The analyses led to a new topology of ground plane that reduces the overall height of the antenna without affecting the electrical performances of the antenna, mainly input matching and radiation patterns. A solution with flat ground plane is also investigated for applications requiring further compactness. Simulations results are presented for the different considered design assuming a frequency plan including radio navigation frequency bands (L1/L5) as well as satellite telemetry frequency band (S-band). Only the lower frequency band is considered as it is the one mostly affected by the ground plane topology.

I. INTRODUCTION

A novel multi-band pyramidal antenna combining radio navigation (combination of GPS and Galileo frequency bands) and telemetry for small satellites (CNES MicroSAT family) was recently introduced in the literature [1, 2]. The antenna is composed of four radiating elements printed on a substrate with low permittivity, each element being disposed on a face of a square-base pyramid supported by an electrically transparent material (polystyrene for example). This material is only used as a mechanical support. Circular polarization is achieved feeding the four elements with a 90 degrees phase progression. The progression of phase in the clockwise or counterclockwise allows choosing between the Right- or Left-Hand Circular Polarization. This is particularly important as telemetry may be either left or right depending on the mission. Adding traps along the radiating elements permit to adapt the length of the element to the different resonant frequencies, thus producing a multi-band behavior. It was found that perforating the ground plane in the area between the feeding points of the four radiating elements improves the input matching of the antenna mainly at the lower frequency but rear radiation is degraded, which may induce undesired interaction with supporting structure and satellite in the case of on-board applications. Therefore, a cut-off open-ended waveguide was initially added to the ground plane. A trade-off is to be found in the design of this waveguide to improve impedance matching at lower frequency while maintain reasonable rear radiation, as detailed in [1].

In this communication, some evolutions on the initial concept are proposed mainly to improve the overall antenna height. Different configurations are compared leading to an interesting solution with a ground plane height reduction of 57% with very similar electrical performances when compared to initial design. A solution with flat ground plane having multiple holes is also found as an improvement over standard non-perforated ground plane design. Input matching performances are intermediate between the poorly matched fully grounded design and the properly matched ground plane with under cutoff open-ended waveguide.

II. PARAMETRIC STUDIES

The different ground plane topology configurations were investigated using CST Microwave studio time domain solver based on Finite Integration Technique (FIT). Performances were investigated at the lower frequency of the initial design, corresponding to the GPS/Galileo Extended E5 band (1.142-1.252GHz) that includes L5, E5a and E5b. This quite large bandwidth for GNSS signals is required for high precision applications. Radiation performances are investigated at 1.189GHz. The main goal of these investigations was to reduce the overall height of the antenna as the ground plane accounts for almost 2/3 of the original design antenna height. While reducing the antenna dimensions, the goal is also to keep acceptable electrical performances and if possible the improvement on the input matching brought by the original design.

A. Antenna with a cylindrical under-cutoff open-ended waveguide

First step in the parametric study was to further investigate the initially proposed configuration illustrated in Fig. 1. Different parameters were studied as the length and radius of the ground plane as well as the height and radius of the cylinder. First, it was found that increasing the ground plane would improve rear radiation but degrade input matching and axial ratio. Moreover, the radius of the ground plane does not shift the resonance frequency of the antenna. Consequently, a good compromise between the rear radiation and the input matching could be found with a reasonable radius. Finally, the

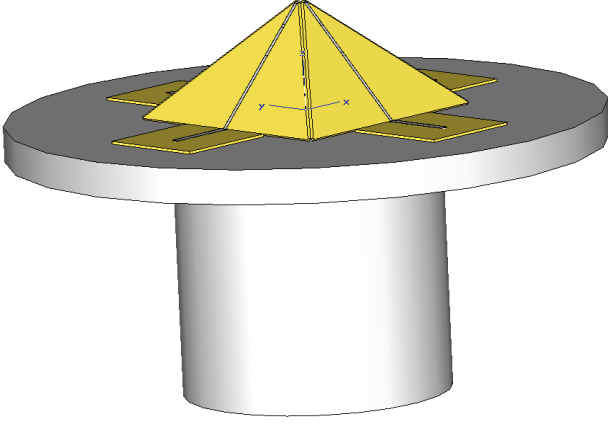


Fig. 1: Pyramidal antenna with under-cutoff open-ended waveguide

influence of the height of the ground plane on the antenna performances is negligible. Therefore, in the aim to reduce the overall height of the antenna and its mass, the height of the ground plane could be adjusted following mechanical constraints without disturbing RF performances of the antenna. In the following analyses, the ground plane has a thickness set to 5mm. Second, the parametric studies showed that the radius of the cylinder is also an important parameter. It actually induces a shift of the resonance frequency. The bigger the radius the lower the resonance frequency. Furthermore, the rear radiation increases and the input matching improves as the radius increases. It appears that the optimal configuration allowing a good compromise between the input matching performances and the radiation pattern performances occurs when the diameter of the cylinder is equal to the length of the square-base of the pyramid, meaning that the radiating elements feeding point is at the edge of the ground plane perforation. The length of the waveguide is also an important parameter as already discussed in [1]. Actually, the length is the main parameter to control the rear radiation and the cross-polarization level of the antenna. Moreover, it does not affect the resonance frequency. For our targeted application that combines GNSS and Telemetry applications, using a cylinder allows to have an input matching 4dB lower than the case with a simple ground plane and the length of the cylinder allows to control the rear radiation and the axial ratio of this antenna (Fig. 2).

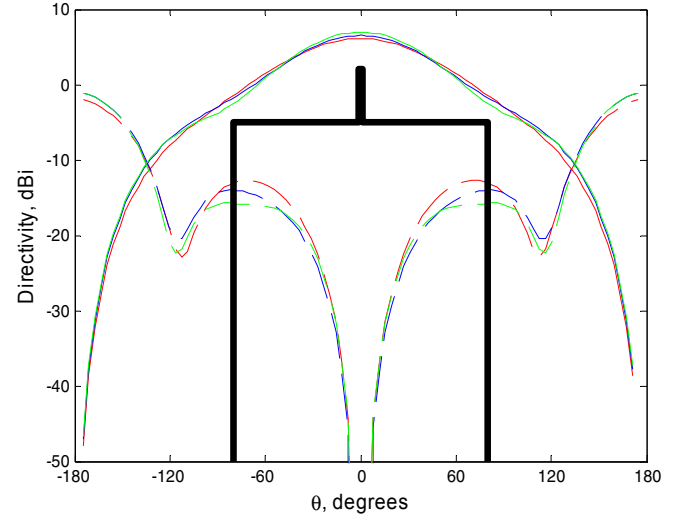


Fig. 2: Comparison of radiation patterns versus length of the cylinder ($f=1220\text{MHz}$) (RHCP: solid lines, LHCP: dashed lines; $L=30\text{mm}$ in red, $L=70\text{mm}$ in blue and $L=90\text{mm}$ in green)

B. Antenna with a conical under-cutoff waveguide

A possible evolution of the antenna is to use a conical waveguide instead of the initial cylindrical waveguide. This configuration was found to achieve very similar performances while leading generally to reduced height. We investigated both complete (Fig. 3) and truncated conical waveguide (Fig. 4). It was found that a truncation is possible without degrading performances, which can be understood by the fact that very little signal propagates through this reduced aperture due to its small size compared to the wavelength.

Starting with the full conical waveguide solution, we investigated the influence of the length of the cone. Actually, it was found that the length of the cone does not influence significantly the resonance frequency (Fig. 5) but impacts the input matching of the antenna. The longer the length of the cone the better the input matching (Fig. 6). However, the increase of the input matching is relatively low compared to the increase of the overall height of the antenna. Consequently, it appears that it is not necessary to use a long cone to ensure good RF performances. Moreover, the rear radiation is equivalent to the rear radiation of the antenna with a simple ground plane (rear directivity around -3.5dB) since the cone “closes” the ground plane and avoids any power leakage. Finally, a cone with a reasonable length (about 50mm) allows a low rear radiation (as a simple ground plane) and a satisfying input matching (equivalent to the matching obtained with a ground plane with cylindrical waveguide with a length of 60mm (Fig. 7).

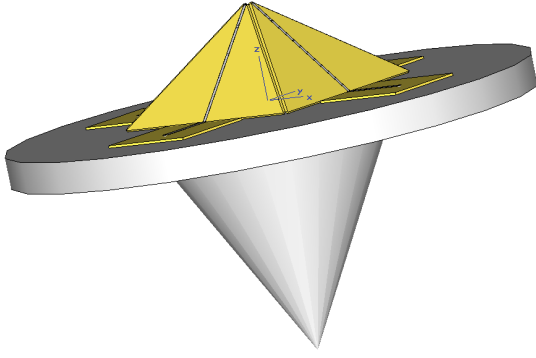


Fig. 3: Pyramidal antenna with complete conical ground plane

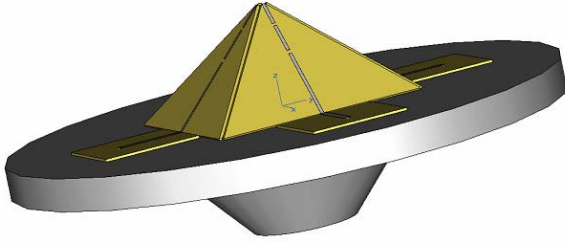


Fig. 4: Pyramidal antenna with truncated conical under-cutoff open-ended waveguide

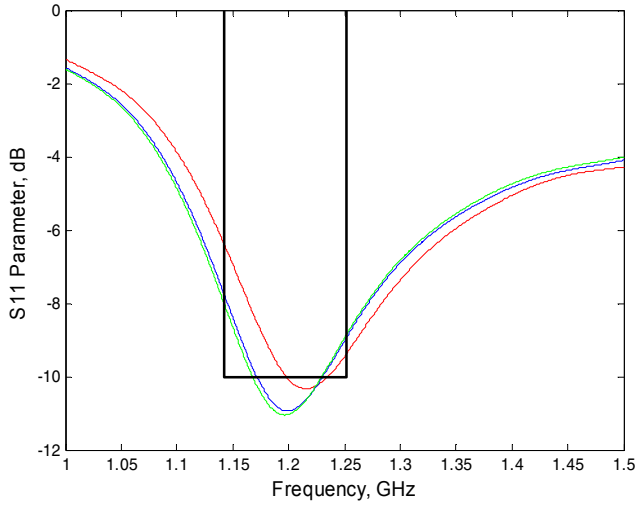


Fig. 5: Comparison of the input matching versus length of cone (L=10mm in red, L=50mm in blue, L=70mm in green)

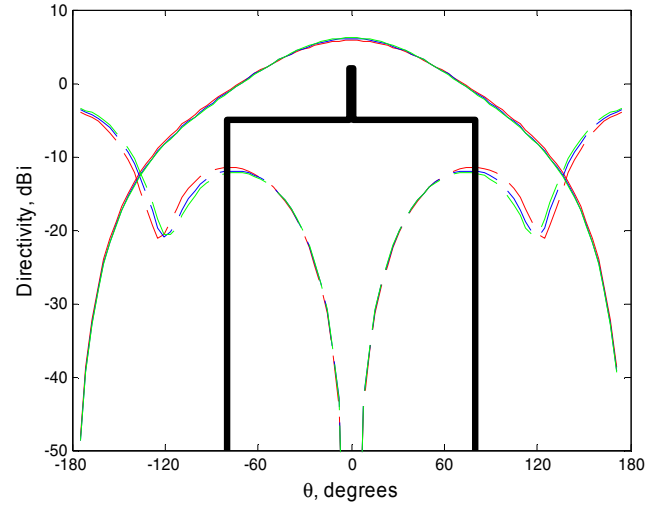


Fig. 6: Comparison of the radiation patterns versus length of cone (RHCP: solid lines, LHCP: dashed lines; L=10mm in red, L=50mm in blue, L=70mm in green)

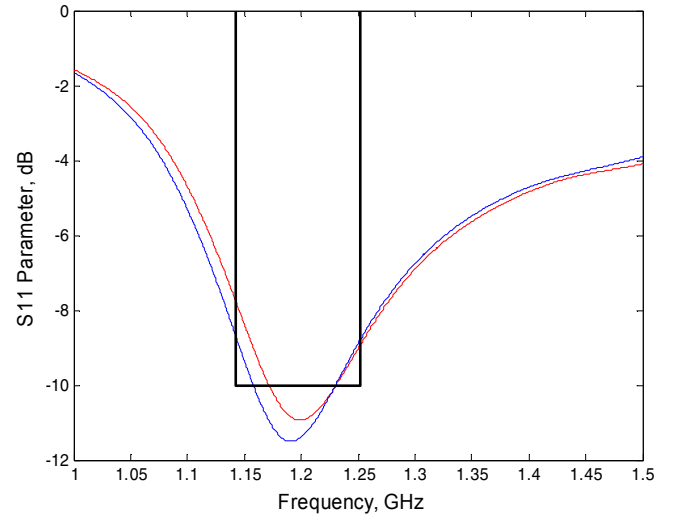


Fig. 7: Comparison of the input matching (Cone L=50mm in red, Cylindrical waveguide L=65mm)

For the second solution, the antenna with a truncated conical under-cutoff open-ended waveguide, the length of the truncated cone and the radius at the open-edge are the two parameters studied. It was showed that the performances of the antenna with a truncated cone are similar to the performances obtained with the complete cone in term of radiation and matching. The length of the cone affects slightly the input matching and the resonance frequency of the antenna. The smaller the radius at the open edge the lower the rear radiation as the solution gets closer to the solution with a complete closed cone. Actually, the termination of the cone does not impact the RF performances of the antenna. Using a truncated cone allows to reduce the length of the cone by a ratio of 3/7 (Fig. 8) resulting in a reduction of 57% on the total height of the antenna.

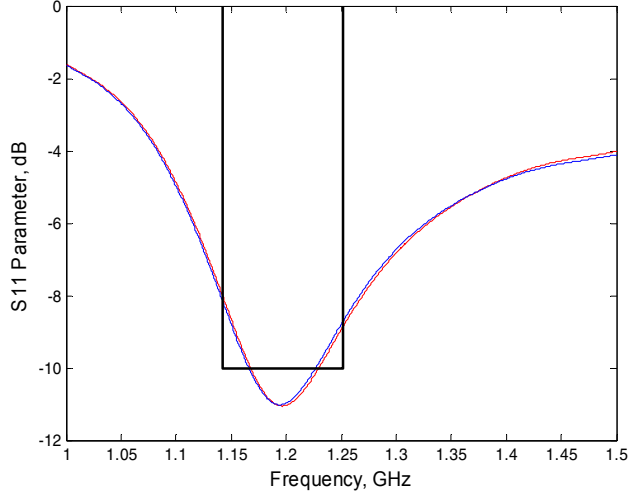


Fig. 8: Comparison of the input matching with a truncated cone ($L=30\text{mm}$ in red) and a complete cone ($L=70\text{mm}$ in blue)

C. Antenna with multiple holes in the ground plane.

An alternative solution found to reduce as much as possible the height of the antenna is to suppress the under-cutoff open-ended waveguide. Obviously, if we keep the configuration with a centred hole reaching to the feeding points of the radiating elements, rear radiation increases significantly. Consequently, we investigated the possibility to replace the large centred hole by several smaller holes in the ground plane. Since these smaller holes are well under cut-off frequency the adjunction of waveguides can be avoided. Basically, considering the thickness of the ground plane, each hole in the ground plane can be seen as being connected to a waveguide with a length equal to the thickness of the ground plane. One can possibly play with this thickness to refine the performances of the antenna.

Fig. 9 gives an example with four circular holes perforated in the ground plane, one hole per radiating element. Obviously, the number and the shape of these holes have a significant impact on the antenna performances. The influence of these parameters was studied. It was found that circular holes generally give better antenna performances than rectangular holes for the input matching and the radiation pattern when the number and the total area of holes are comparable. It was found that, for a constant number of holes, the bigger the hole's radius the better the input matching but at the same time the higher the rear radiation. For a constant total area of holes, the increase of the number of holes improves the rear radiation of the antenna but there is no monotonous variation of the input matching versus the number of holes (Fig. 10). It appears that the best input matching is obtained with one hole.

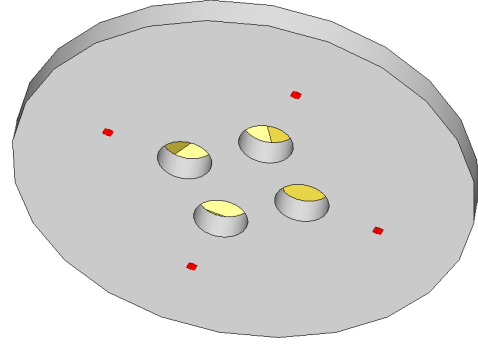


Fig. 9: Pyramidal antenna with multiple holes in the ground plane

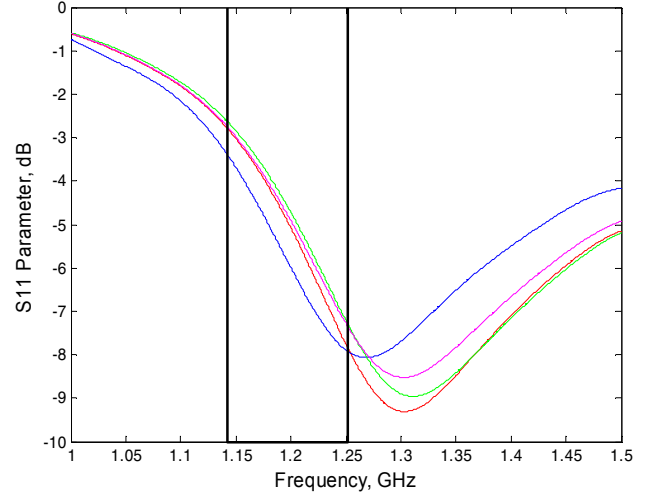


Fig. 10: Comparison of the input matching versus number of holes (1 hole in red, 2 holes in blue, 4 holes in green and 8 holes in magenta)

Finally, this solution was found to be an intermediate between previous configurations and the antenna with a flat non-perforated ground plane. But since the input matching improvement is not as significant as with the under-cutoff waveguides, this solution is to be used only when strong constraints apply on the antenna dimensions.

III. COMPARISON OF THE DIFFERENT TOPOLOGIES OF GROUND PLANE

A. Input matching performances

Different examples from previously described configurations are reported here. The antenna with cylindrical under-cutoff open-ended waveguide is the best solution in term of input matching (Fig. 11). However, the solution with the conical waveguide (truncated or not) presents quite similar performances with an overall height of the antenna reduced by 57% for selected configurations when compared to the cylindrical configuration. Moreover, we can notice that a perforated ground plane induces a frequency shift as the non-perforated configuration as a resonant frequency around 10% higher. It means that for a same operating frequency, non-perforated ground would require longer radiating elements than configurations with perforated ground plane resulting in

an antenna's height slightly increased due to the pyramidal arrangement of these radiating elements.

As already discussed, the configuration with multiple perforated holes results in an intermediate solution both in performances and in frequency shift.

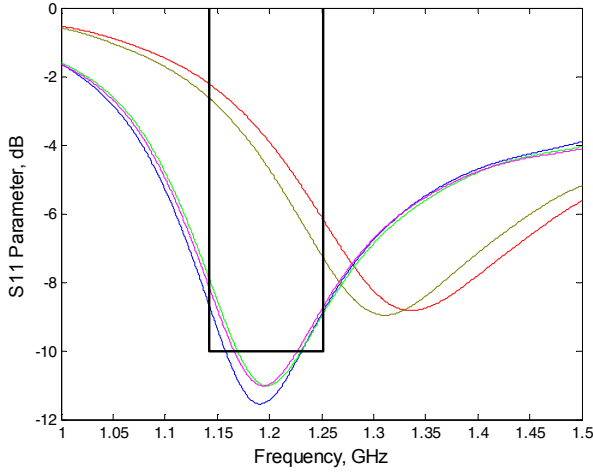


Fig.11: Comparison of the S11 parameter of the antenna versus the different topologies of ground plane (non-perforated ground plane in red, perforated ground plane with 4 holes in brown, truncated conical waveguide L=30mm in magenta, complete conical waveguide L=60mm in green, cylindrical waveguide L=70mm in blue)

B. Radiation patterns

Different examples from previously described configurations are also reported here. The antenna with cylindrical under-cutoff open-ended waveguide is the solution with the highest rear radiation (Fig. 12) but the best axial ratio over the angular range $[-80^\circ, 80^\circ]$. The antenna with a truncated conical waveguide offers a better rear radiation (a directivity around -3.5dBi instead of -1.2dBi for the cylindrical waveguide) but a higher axial ratio ($<0.72\text{dB}$ instead of $<0.55\text{dB}$ for the cylindrical waveguide).

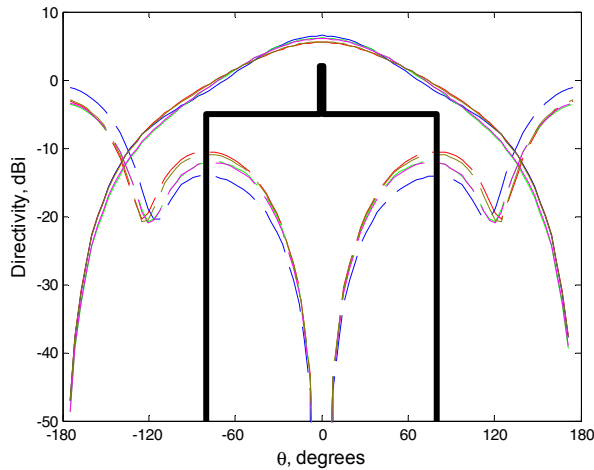


Fig.12: Comparison of the radiation pattern of the antenna versus the different topologies of ground plane (RHCP: solid lines, LHCP: dashed lines; non-perforated ground plane in red, perforated ground plane with 4 holes in brown, truncated conical waveguide L=30mm in magenta, complete conical waveguide L=60mm in green, cylindrical waveguide L=70mm in blue).

IV. CONCLUSION

The parametric studies of the different topologies of ground plane presented in this paper confirmed the potential of an original topology of ground plane, namely the ground plane with the truncated conical under-cutoff open-ended waveguide. The design of this ground plane allows ensuring good RF performances. The antenna with conical ground plane presents input matching performances equivalent to the performances obtained with a ground plane having a cylindrical waveguide while having rear radiation performances equivalent to the non-perforated ground plane. Actually, this new ground plane allows to minimize the rear radiation and have a sufficient input matching with a reduced size by 57% relatively to the antenna with cylindrical waveguide. Only the axial ratio is slightly degraded relatively to the antenna with cylindrical waveguide but remains good enough for most GNSS applications.

This new topology of antenna that only affects the ground topology keeps obviously all the advantages of the initial solution, namely a simple design and flexibility on the definition of the frequency plan as well as the choice of polarization. This concept was validated on GPS and telemetry applications but could be extended to another applications.

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