J. of Electromagn. Waves and Appl., Vol. 25, 857–868, 2011

MONOPULSE CIRCULARLY POLARIZED SIW SLOT ARRAY ANTENNA IN MILLIMETRE BAND

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Abstract—A circularly polarized slot array antenna in millimetre band is presented. A cosecant amplitude coverage in the elevation plane, as well as a 6° tilted monopulse pattern in the azimuth plane, is obtained. The radiating slot array is implemented over substrate integrated waveguides (SIW). A microstrip feeding network with coaxial to SIW transitions is designed for the elevation radiation pattern. The monopulse feed is implemented in metallic rectangular waveguide, which is connected to the elevation feeding network by means of microstrip to waveguide transitions. A gain peak value of 28.6 dBi and 79% of efficiency at 36.7 GHz has been obtained in the specified operation band (36.7–37 GHz) for a manufactured antenna prototype. Likewise, the top measured axial ratio is 1.95 dB at 36.85 GHz.

1. INTRODUCTION

Slotted rectangular waveguide arrays (SRWA) have been widely used in microwave range due to their very low losses properties. Linearly polarized resonant arrays of longitudinal slots in the broad wall of the rectangular waveguide have mainly been implemented [1–3]. Two 45° inclined and quasi-orthogonal slots, with a $\lambda_g/4$ separation

Received 16 December 2010, Accepted 10 January 2011, Scheduled 20 January 2011
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between them (λ_g is the waveguide wavelength), have been proposed as circularly polarized (CP) single element for SRWA [4], which had been previously used in radial line slot antennas [5–8]. However, in order to improve mechanical precision and reduce manufacturing costs, the substrate integrated waveguide (SIW) technology [9, 10] has been incorporated to SRWA. [11–14] are some examples of resonant linearly polarized slotted substrate integrated waveguide arrays (LP-SSIWA). A circularly polarized design (CP-SSIWA) is presented in [15]. In this case, the antenna consists of two $+45°/-45°$ LP-SSIWA, which are combined by a 90° hybrid coupler to achieve CP. The radiating elements are 45° inclined reflection cancelling slot pairs [16].

In this paper, a new slotted CP single element for SIW is presented. The slot special features of [4] (polarization) and [16] (reflection) are combined and applied from rectangular waveguide (RW) to SIW. A comparative between the proposed and the traditional two slot element of [4] is discussed in Section 2.1. Likewise, a CP-SSIWA application of the new element is presented in Section 2.2, with experimental results in Section 3. According to specifications, the antenna is part of a signal identification system, which operates from 36.7 to 37 GHz. A cosecant elevation and a 6° tilted monopulse [17] azimuth pattern are required.

The antenna consists of three parts (Fig. 1(a)): a non-resonant CP-SSIWA (Fig. 1(b)), a microstrip feeding network to obtain the desired cosecant elevation pattern (Fig. 1(c)), and a monopulse network in RW technology for the azimuth coverage (Fig. 1(e)). From a manufacturing point of view, the antenna is divided in three modules. Module 1 contains the CP-SSIWA and the radome at the top side, while the microstrip elevation feeding network is placed at the bottom side. The connection between them is made by means of microstrip to SIW transitions. These transitions are metallic pins soldered in one side to the microstrip lines and partially inserted in the SIW at the opposite end. Module 2 contains a metallic cover for the microstrip circuit (Fig. 1(d)), where the air gap between cover and circuit is 3 mm. Module 3 is the RW monopulse network, which is designed with a branch-line coupler and a 90° phase extra path between the sum (Σ) and difference (Δ) input ports. A modular structure is required, with independent access to the elevation and azimuth networks by means of WR-28 waveguide flanges. Therefore, microstrip to RW transitions are implemented in the elevation feeding network, as RW paths are necessary to include the required WR-28 flanges. All the RW paths in the antenna have been implemented with a H plane configuration (loss improvement), and mechanized in two pieces, which are joined by metallic screws at the middle of the RW vertical walls.

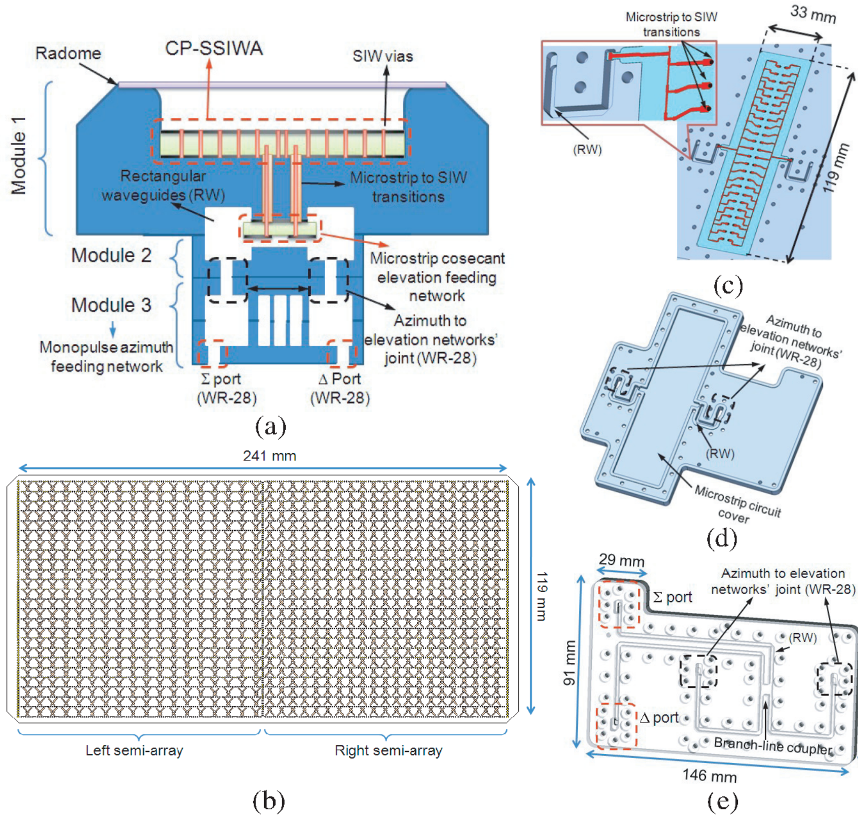
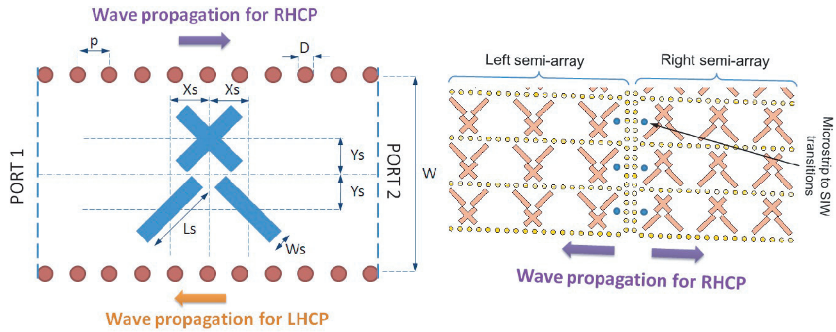


Figure 1. Geometry of the designed antenna: (a) global structure side-view, (b) CP-SSIWA, (c) microstrip cosecant elevation feeding network, (d) module 2: cover of the microstrip elevation network, (e) monopulse azimuth feeding network.

2. ANTENNA DESIGN

2.1. New CP Slotted Single Element

A new circularly polarized slotted element is introduced in the CP-SSIWA. As Fig. 2(a) shows the element consists of four slots, and represents a combination of [4] and [16] radiating elements. In order to achieve circular polarization, two orthogonal slots with $+45°$ and $-45°$ orientation over the waveguide longitudinal axis have been used in the state of art [4]. A $\lambda_{gSIW}/4$ (λ_{gSIW} is the SIW wavelength) separation between both slots originates the $90°$ feeding



(a) (b)

Figure 2. New CP slotted radiating element geometry in SIW: (a) top view. Virtual waveguide ports (1 & 2) for S-parameter simulations, (b) single element placement in CP-SSIWA for desired RHCP.

phase difference between the two orthogonal linearly polarized E-field components corresponding to each radiating slot. Likewise, a reflection cancelling slot is added to each radiating slot, as proposed in [16], which are separated Xs (horizontal) and $2Ys$ (vertical) from the original radiating slot pair. According to Fig. 2(a) scheme the electrical properties of the new element (four slots) have been analyzed and compared with the element in [4] (two slots). The geometrical equivalences between RW and SIW [18] have been applied to reduce time simulation in the CST Microwave Studio software.

The SIW parameters are: 1.575 mm thick teflon laminate ($\varepsilon_r = 2.17$), $W = 5$ mm (which corresponds to an equivalent RW aperture of 4.73 mm), $D = 0.5$ mm (via diameter), $p = 1$ mm (via separation). To radiate right hand circular polarization (RHCP) the wave in the SIW must be propagated from port 1 to 2 (Fig. 2(a)), while for a left hand sense (LHCP) the wave must be propagated from 2 to 1. Fig. 3 shows the amplitude of the reflection ($S_{1,1}$), transmission ($S_{2,1}$) and coupling parameters of the radiating slots as a function of the slot length (L_s). Under the assumption of no losses in Fig. 2(a) simulation scheme, the coupled power to the slots, which is fully radiated, is defined as:

$$Coupling = \sqrt{1 - (|S_{1,1}|^2 + |S_{2,1}|^2)} \quad (1)$$

According to Fig. 3 results, the four slot element presents a bigger radiating capability for a smaller size. To obtain the same coupling value the required length (L_s) in the four slot case is significantly shorter in comparison with traditional two slots. As in the array design will be demonstrated, this is an essential property for the antenna performance.

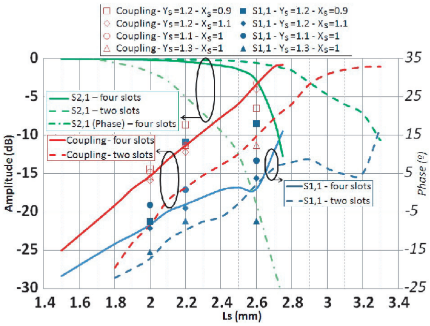


Figure 3. Amplitude of transmission ($S_{2,1}$), reflection ($S_{1,1}$) and coupling parameters (left axis), as well as phase of $S_{2,1}$ (right axis) as a function of slot length (L_s), with $X_s = 1\,\text{mm}$ and $Y_s = 1.2\,\text{mm}$ as nominal values. Parametric study (X_s and Y_s variation). Traditional two slot versus new four slot CP radiating element.

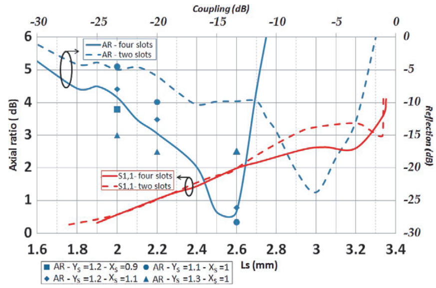


Figure 4. Axial ratio (AR) as a function of slot length (L_s) and slot reflection ($S_{1,1}$) as a function of slot coupling, with $X_s = 1\,\text{mm}$ and $Y_s = 1.2\,\text{mm}$ as nominal values. AR parametric study (X_s and Y_s variation). Traditional two slot versus new four slot CP radiating element.

Figure 4 summarizes the axial ratio (left axis) versus the slot length (down axis) of the new CP radiating element in comparison with the traditional two slot configuration. This axial ratio is calculated at 36.85 GHz in broadside direction. Likewise, a comparative of the reflection (right italics axis) as a function of the coupled power (top italics axis) to the two types of radiating elements is also included. As Fig. 4 shows, a wider range of slot lengths can be implemented for an optimal polarization behavior (3 dB axial ratio criteria) in the novel single element. Short lengths in two slot element generate bigger polarization deterioration than in the case of four slots. Moreover, as $S_{1,1}$ curves in Fig. 4 show, the reflection level is significantly lower for high coupling values (-15 to -2 dB range) in the proposed slot structure.

Figure 5 shows a similar frequency response for two and four slot elements, with a reasonably stable behavior in both cases. Nevertheless, the curve slop variation is slightly bigger for the four slot element in the AR response, while is smaller in reflection. The single element application to this kind of progressive wave array structures (Fig. 1(b)), leads to serial antenna schemes and narrow-band response [4].

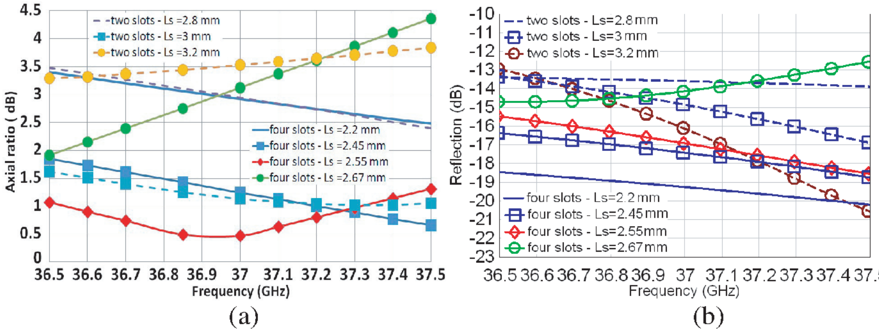


Figure 5. Two and four slot element behavior as a function of frequency for fixed slot lengths (L_s). $X_s = 1\,\text{mm}$ and $Y_s = 1.2\,\text{mm}$ as nominal values: (a) axial ratio, (b) reflection coefficient.

Curves from Fig. 3 to Fig. 5 have been computed for $X_s = 1\,\text{mm}$ and $Y_s = 1.2\,\text{mm}$, which has been found as the optimum geometry in terms of reflection and axial ratio behavior. The slot width W_s (not a noticeable influence) is 0.5 mm. Nevertheless, a parametric study is also included for $L_s = 2$, 2.2 and 2.6 mm slot lengths, in order to show the $S_{1,1}$ (solid marks in Fig. 3), coupling (empty marks in Fig. 3) and axial ratio (solid marks in Fig. 4) variation as a function of the slot geometry. Therefore, although in this paper X_s and Y_s have been fixed independently of the slot lengths, these parameters can be modified for each slot length in order to optimize the polarization and reflection array performance.

2.2. Array Design

The CP-SSIWA is divided in two semi-arrays in order to properly generate the Σ and Δ patterns of the monopulse azimuth coverage (Fig. 1(b)). The elevation microstrip feeding circuit (which in fact is composed of a microstrip network for each semi-array) create outward wave propagation in the SIWs as Fig. 2(b) indicates. As this wave propagation is in opposite direction for each semi-array, slots on the left half are 180° rotated with respect to the right one. Thereby, according to Fig. 2(a) criteria, the slot placement to obtain in the array the desired RHCP is the one shown in Fig. 2(b). For a broadside pattern one λ_{gSIW} slot separation in horizontal direction should be implemented. Nevertheless, in this antenna a 6° tilted azimuth pointing angle is specified. Therefore a progressive phase difference between horizontal adjacent single elements is required, which is reached with a smaller ($< \lambda_{gSIW}$) for the left semi-array,

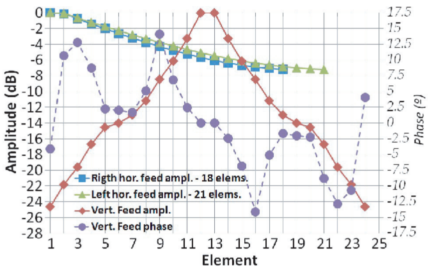


Figure 6. Amplitude and phase feeding coefficients for the monopulse azimuth and cosecant elevation array patterns.

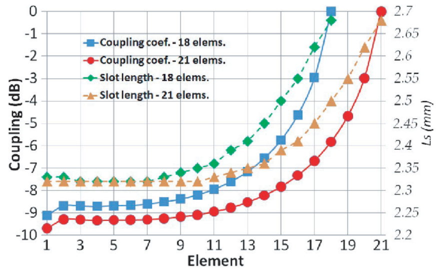


Figure 7. Coupling (left axis) v slot lengths (right axis) for the SIW azimuth semi-arrays.

and bigger ($> \lambda_{gSIW}$) slot separation. In this way, the main beam of the antenna is pointed in the same angle direction, besides the opposite direction of the propagated wave in both antenna halves. In this case, the average horizontal slot separations are: $0.72\lambda_0$ ($0.92\lambda_{gSIW}$) in the left semi-array and $0.86\lambda_0$ ($1.08\lambda_{gSIW}$) in the right half, which respectively correspond to $+27°$ and $-32°$ progressive phase differences (λ_0 is the air wavelength). These separations are slightly adjusted to compensate the variation of the transmission phase with the slot length increasing ($S_{2,1}$ phase in Fig. 3). The horizontal feeding amplitude in Fig. 6 for the monopulse pattern is achieved by means of the slot length (L_s) variation according to the required coupling (Fig. 7). These coupling coefficients have been obtained as authors shown in [19]. Likewise, a cosecant pattern is specified in the elevation plane. A microstrip circuit is used to obtain the required feeding coefficients in Fig. 6, where the right axis corresponds to the phase. Therefore, according to the gain (> 27 dBic) and radiation pattern requirements a 39 (columns) $\times$24 (rows) CP-SSIWA has been designed. The 39 columns are divided in two equal size semi-arrays of 21 (left half) and 18 (right half) elements. The row separation is defined by the SIW width ($W = 5$ mm). Neglecting losses in the dielectric, all the propagated power in the SIW is fully radiated. Therefore, last elements in both left and right semi-arrays are designed as matched loads (composed by the new CP slotted element and a final short circuit in each SIW end).

According to Section 2.1 study, the equivalent slot lengths for the same CP-SSIWA with traditional two slot single elements would have led to dimensional problems for high coupling values (besides a deterioration of the input reflection coefficient), due to the proximity of slot edges to the vias of the SIWs.

3. EXPERIMENTAL RESULTS

A prototype of CP-SSIWA has been manufactured (Fig. 8) based on Fig. 1 scheme, and according to specifications and radiation pattern requirements detailed in previous sections. The electrical characteristics of the antenna have been measured. As Fig. 9(a) shows a peak value of −14.5 dB (Σ port) and −15.8 dB (Δ port) in the desired band (36.7–37 GHz), as well as −13.5 dB (Σ) and −15 dB (Δ) in the extended measurement band (36.5–37.5 GHz) is achieved for the reflection coefficient of the prototype antenna.

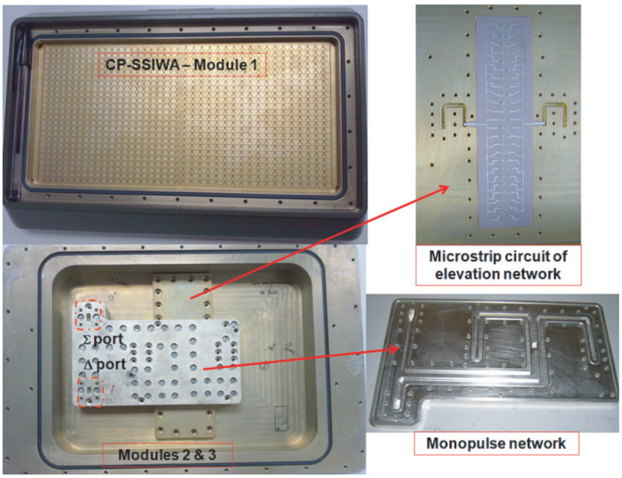


Figure 8. Manufactured CP-SSIWA prototype.

A good agreement with the full wave simulations (CST) is achieved. Likewise, Figs. 9(b)–(d) present the Σ elevation, as well as the Σ and Δ azimuth copolar (RHCP) measured radiation patterns at the central frequency of the band (36.85 GHz). The elevation pattern has been obtained by previously pointing the antenna to the main beam (6°) in the azimuth plane (conical cut plane). The desired cosecant elevation coverage is almost obtained although side lobe level increase in both elevation and azimuth patterns are shown. The manufacturing via process over PTFE substrate is not sufficiently optimal, and incomplete vias were detected. Therefore, the coupling between adjacent SIWs increases in comparison with the simulated antenna. The circularly polarized RHCP and LHCP gain components are shown over the frequency at the main beam angle in Fig. 10. A frequency displacement of the optimal polarization response is observed in comparison with simulations, as axial ratio results in Fig. 11 also confirm.

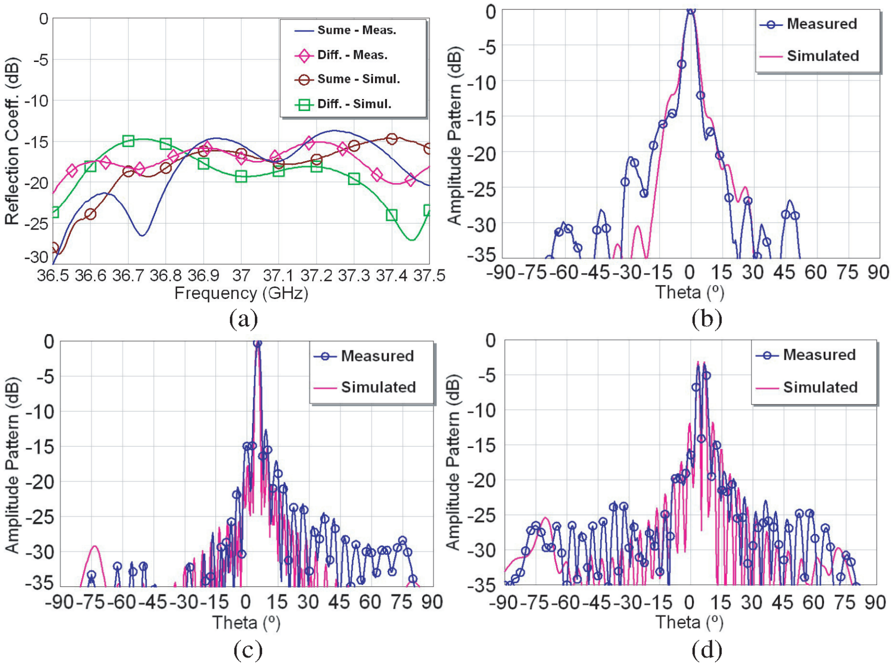
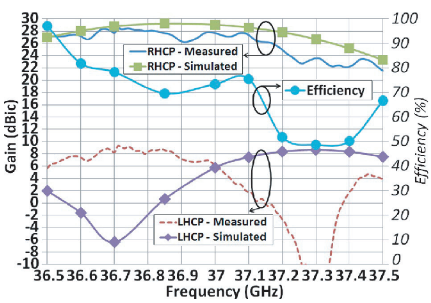


Figure 9. Measured v simulated electrical behavior of the prototype antenna: (a) reflection coefficient, (b) elevation, (c) Σ azimuth, and (d) Δ azimuth radiation patterns (RHCP component at 36.85 GHz).



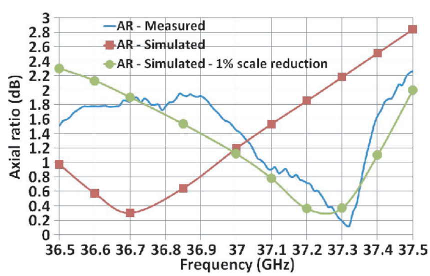


Figure 10. Measured v simulated RHCP and LHCP gain components of the prototype antenna. Measured efficiency.

Figure 11. Measured v simulated antenna axial ratio.

The tolerance of the etching manufacturing process at these frequencies seems to be not sufficiently precise. As Fig. 11 shows, the prototype presents a 1% scale reduction according to designed antenna. Nevertheless the measured axial ratio is better than 2 dB in the entire measurement band. Finally, a 70% of efficiency has been computed as minimum value in the desired frequency band (36.7–37 GHz), as Fig. 10 shows. A spurious radiation effect of the vias in the microstrip network has been detected, which affects to the antenna efficiency. The substitution of the microstrip for a SIW elevation feeding network would avoid this effect and improve the antenna efficiency. Nevertheless, the prototype results indicate a satisfactory behaviour of the new CP four slot element in array applications.

4. CONCLUSION

A new four slot single element is presented for CP-SSIWAs. A slot length reduction, as well as a reflection and axial ratio improvement in comparison with traditional two slot element, is achieved to obtain the same coupling response. This new slotted element has been tested in a high gain array antenna prototype. A 6° tilted monopulse pattern in the azimuth plane and cosecant pattern in the elevation plane are implemented. A gain peak value of 28.6 dBi and 79% of efficiency at 36.7 GHz have been obtained in the operation band (36.7–37 GHz). The measured results are compared with full wave simulations. Satisfactory reflection and polarization results have been achieved. Nevertheless, manufacturing precision problems lead to inappropriate side lobe levels. Likewise, due to losses considerations, the use of microstrip technology in the elevation feeding network reduces the antenna efficiency. All these aspects will be considered in future research steps.

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