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Array Elements for LEO SatCom Payloads

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***Abstract*—With each generation of mobile communications, there is an exponential demand for both data transmission and a larger coverage footprint. One of the proposed solutions to these needs may be the deployment of communications via low orbit satellites, LEO SatCom. For this purpose, different types of antennas have been reviewed, such as waveguide-based aperture and All-Metal Vivaldi antenna.**

Keywords—Non-Terrestrial Network (NTN), array, LEO satellite, waveguide, Vivaldi, PUMA

I. Introduction

The development of Non-Terrestrial Network (NTN) systems has become a solution to complement the current deployed cellular terrestrial networks to satisfy the demands of worldwide coverage, greater speed of data transfer and ensuring service availability, continuity, and scalability [1]. In this scenario, the new generation of mobile communication network is expected to support both cellular terrestrial and NTN systems to provide full broadband services in wide coverage and motivate the emergence of new applications [2]. NTN is based on boost the paradigm of using air segments where either satellites or airborne act as node in the already deployed terrestrial network.

From an architecture point of view, satellites in a GEO orbit can offer global coverage, as the satellite footprint is much larger. However, its latencies are considerably higher compared to a lower orbit, because of its longer path. In contrast, from a LEO orbit, the coverage area is much smaller, and, because of its speed, it becomes a challenge to track from a ground station [3]. However, the latter orbit has become more popular in recent years to meet the requirements of a more discerning demand. One of the first suggestions that may come to mind is to extrapolate the use of antennas from a GEO orbit to a LEO orbit, such as reflectors. However, mechanical scanning is not applicable in LEO due to its size and weight, crucial variables in a future massive deployment of LEO satellites [4].

Nowadays, thanks to recent technological advancements in the space industry and academia, it has been demonstrated that phased arrays using electrical beam steering or beamforming are beneficial in terms of cost, complexity and overall system performance compared to antenna apertures with mechanical steering. For this reason, a phased array antenna using beamforming has been adopted as the most interesting approach in the millimeter wave band [5].

The fundamental characteristics in space radiation elements are to support high power capabilities while having minimal losses. In this case, waveguides are a good candidate for design [6]. In addition, it has been proposed ultra-wideband antennas such as Vivaldi antenna [5] or Planar Ultra-wideband Modular Antenna (PUMA) [7] as a solution for the millimeter wave band featuring very large bandwidth, low cost, easy to manufacture and good overall performance.

This paper is organized as follows. Section II describes the main requirements that could be met by the proposed designs. Furthermore, it presents two proposed phased array antenna designs for LEO SatCom: waveguide-based aperture and All-Metal Vivaldi antenna. Section III shows the performance of both array antenna designs. Section IV concludes this.

II. Antenna Designs

For LEO satellite communication, the highest possible scanning angle is required. In this work, designs have been made to be able to scan up to a range of ± 60° without grating lobes in Ka-band (17.7–20.2 GHz). The scanning angle determines the maximum periodicity between radiating elements. According to (1), where θ_{max} corresponds to 60º and $\lambda_{20.2\ \mathrm{GHz}}$ is the wavelength of the maximum operating frequency in free space, the maximum element spacing, p, is 7.8 mm.

$$p \leq \frac{\lambda_{20.2\ \mathrm{GHz}}}{1+\sin\theta_{\max}} \quad (1)$$

A. Waveguide-based aperture

Waveguides are generally metallic devices with an internal cavity, capable of guiding electromagnetic waves from one point to another. This kind of guides are very useful in space applications because it offers good performance with low losses, reduced weight and cost, leading to large-scale production [8].

As mentioned above, beam scanning is necessary in LEO orbit and focusing all the energy on the same direction is essential, thus avoiding secondary lobes. In order to have a lobe scan free of grating lobes, it is necessary to reduce the spacing between elements, analyzed in (1).

From the restriction of the maximum allowed period between cells to avoid field leakage in undesired directions and the waveguide geometry, the cut-off frequency can be computed. However, this cut-off frequency may not be sufficient depending on the frequency band in which we want to transmit or receive, it is usually above this frequency band for simple square waveguides.

There are different techniques to reduce this cut-off frequency. One of the first ideas is to introduce dielectric material into the waveguide cavity itself. In this way, what is achieved is an increase in the relative permittivity and, therefore, a reduction in the transmission velocity. This reduction implies, in turn, a reduction in the cut-off frequency [9].

However, the introduction of dielectric material in this kind of applications, such as in space, generates different problems in the medium and long term. Due to the losses of the dielectric material, one of the main problems is the dissipation of energy through them, as high temperatures are generated which can fracture or break the front-end integration electronics [10].

Another technique to reduce the cut-off frequency is trying to increase the effective length of the waveguide through ridges [11]. Ridge waveguides solve the problems of reduced bandwidth in waveguide structures with limited widths. The result is lower cut-off frequencies, a wide single-mode operational range and reduced impedance [12]. In this sense, the electric field is confined along the ridge or embedded between two facing ridges, known as double-ridge [13].

In this way, no dielectric materials are introduced, and everything is defined in its design. Its accuracy, therefore, will be defined by the manufacturing and assembly process, where there may be differences that corrupt the optimum performance of the antenna [14].

In this context, a square structure has been proposed, using elements such as ridges [15] to work in the Ka-band, which also has an even symmetry, shown in Fig. 1. The aim is to be able to excite these cells by means of two independent ports in each of them, thus achieving that the first two fundamental modes are equal and being able to work with circular polarization, a key concept in space communications [16].

Fig. 1. Square aperture with four ridges loaded.

B. All-Metal Vivaldi array element

Ultrawideband (UWB) electronically scanned phased arrays has been adopted for many modern radar and wireless communications in the recent past [17].

The flared-notch (Vivaldi) or tapered-slot antenna is the most widespread use radiator element in UWB phased arrays for its excellent wide-band, matching over wide scan angles and ease and low-cost fabrication features [18] [19]. On the downside, they feature electrically long profiles (normally a wavelength or more at the highest frequency of operation) whereas it causes considerable high cross polarization when scanning off the principal axes [19].

For over 30 years, they were made of printed-circuit board (PCB) which featured low cost, low weight and simple to manufacturing [20]. In contrast, they add dielectric losses and consequently, degrades the radiation efficiency. As a result, Rick W. Kindt and W. R. Pickles has done a lot of research on Vivaldi antennas and proposed an All-Metal design which overcome the aforementioned drawbacks [19] [20]. The All-Metal Vivaldi antenna features good power handling capabilities, less losses compared with the dielectric substrate and so higher radiation efficiency [21].

As an alternative to waveguide apertures, a dual polarized All-Metal Vivaldi antenna element have researched to provide a compact, high modularity and cheap dual polarized antenna element for phased array applications for satellite communications in the Ka-band. For our initial validation study, a double alongside (egg crate) All-Metal Vivaldi antenna array is proposed as a solution to provide circular polarization and beam steering array in the Ka-band with scan angle of ± 60°.

The unit cell consists of two alongside All-Metal Vivaldi antenna. Each unique element consists of elliptical tapered flares, and a circular cavity. The resonant cavity is added to achieve broadband impedance matching. In order to join both singles elements a rectangular box is added among them, reducing the dimension of the width of the unique element by its thickness dimension.

The unit cell is shown in Fig. 2 and follows the design in [22] [23], but designed to operate at the frequency band of the satellite communication downlink, Ka-band. The elements dimensions are 6.8 mm ($\lambda_{20.2\ \mathrm{GHz}}/2.18$) wide, 1 mm ($\lambda_{20.2\ \mathrm{GHz}}/14.85$) thick and 6 mm ($\lambda_{20.2\ GHz}/2.48$) tall. The square grid period in E-plane and H-plane is 7.8 mm, corresponding approximately to λ/2 spacing at 20.2 GHz.

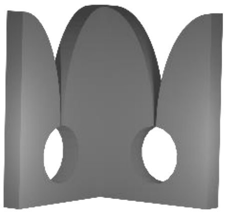

Fig. 2. Double alongside (egg crate) All-Metal Vivaldi antenna.

As has been mentioned previously, Vivaldi antenna suffers from degraded cross-polarization in the D-plane, whereas it is caused by the height dimension of itself, and it worsen as much higher is. In this study, as an initial approach, it has been focused on designing a Vivaldi antenna element with a low profile to reduce the high polarization by keeping a wide impedance match over a wide scan angle. The feeding of this initial design is based on the approach on [22] [23] through using a balance slot line to excite the tapered flares.

III. Simulated Results

A. Quadridge element

The boundary conditions applied to the quadridge are those of a unit cell, simulated as an infinite matrix in both dimensions in CST software. The dimensions applied to the design of Fig. 1 are given in Table 1. The values of the ridges have been selected such that the operating band is within the limits of the first and third mode cut-off frequencies.

Active Reflection Coefficient (ARC) for different scanning angles, from 0º up to 60º, are detailed in Fig. 3. In the E-plane we can observe the first mode cut-off frequency around 17.58 GHz while the third mode cut-off frequency is around 20.47 GHz. One of the reasons why the curves are not smooth when scanned at higher angles is because the upper mode cut-off frequency is quite close to the upper limiting frequency of the Ka-band. Also, when we scan at 60º, all the signal is reflected at 20 GHz due to a scan blindness, thus reducing the operational working band.

One possible solution to overcome scan blindness is to add a lid over the array aperture. In this way, the scan blindness will not be attenuated, but displaced from the operational band. Another possible solution to improve these curves could be to change one of the symmetry planes of the two-dimensional array, i.e., changing the array lattice. In this way, the coupling will act differently and the scan blindness that occurs at 60º could be attenuated. Both solutions could solve the problem, but different factors would have to be taken into account since, if there is a limitation in dimensions, it is difficult to include a lid. However, changing the lattice array can be complicated in terms of the electronics added to the front-end integration.

In contrast, in the H-plane, curves are smooth in the whole band, decreasing its performance when we scan from the zenith to higher angles, up to 7 dB of difference.

TABLE I. DESIGN PARAMETERS OF THE ANALYSED QUADRIDGE

Parameter	Description	Value (mm)
A_w	Aperture width	6.8
A_h	Aperture height	6.8
R_w	Ridge width	1
R_h	Ridge height	1.5
m	Margin between cells	1
p	Period	7.8

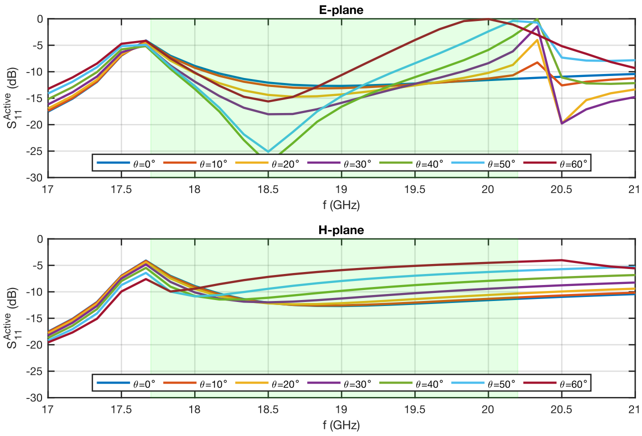

Fig. 3. S_{11}^{Active} (dB) for the quadridge for different scanning angles at E and H planes.

B. All-Metal Vivaldi array element

A unit cell boundary condition is used to simulate the antenna element under the infinite array assumption. The dimensions used in the design of Fig. 2 are those listed in Table 2.

The scan performance of the proposed design through the ARC in an infinite array for the E-plane and H-plane are provided in Fig. 4. These results show how well the design is matched across the operational frequency band for broadside and high scan angles for E-plane and not entirely for H-plane.

For the proposed Vivaldi antenna element, at E-plane with scan angles up to 60º provides VSWR < 2 (S_{11}^{Active} < -10 dB), whereas at H-plane up to 50º scan VSWR < 3 (S_{11}^{Active} < -6 dB) and VSWR < 4.8 (S_{11}^{Active} < -3.8 dB) for 60º scan angle. On first thought, the H-plane behavior is smooth compared with the E-plane but providing worst performance. Hence, at H-plane the VSWR is still poor, and it should be improved to provide better impedance matching bandwidth at the operational frequency band. One potential solution to solve the lack of matching bandwidth is to adopt other cavity shapes.

Furthermore, it is important to mention that the design could work from 12.6 to 20.4 GHz and 14.7 to 20.4 GHz at the E-plane and H-plane respectively with the same performance as the operational frequency band. Due to the appearance of the grating lobes, some discontinuities appear above 20.5 GHz, while reducing the matching bandwidth outside the operational frequency band. The simulated cross polarization levels are still higher in the non-principal plane, specifically close to 60º steering angle, having a cross polarization close to 0 dB.

TABLE II. DESIGN PARAMETERS OF THE ANALYSED VIVALDI

Parameter	Description	Value (mm)
H	Element height	6
W_e	Element width	6.8
W_a	Aperture width	7.8
C_r	Cavity radius	1.5
Ch	Cavity height	4
T	Element thickness	1

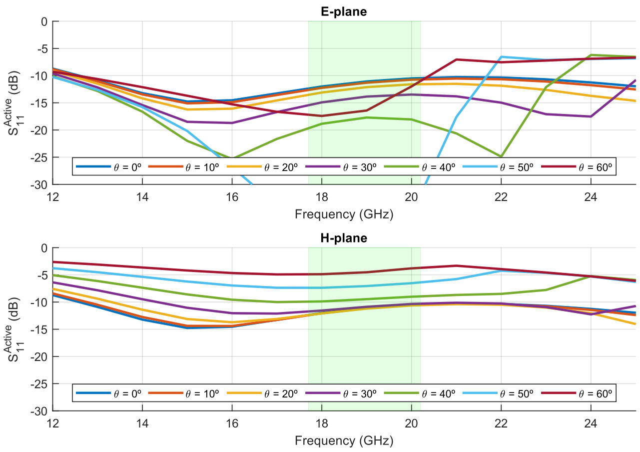

Fig. 4. S_{11}^{Active} (dB) for the Vivaldi for different scanning angles at E and H planes.

IV. CONCLUSION

This paper has addressed some key ideas about antennas for LEO SatCom, especially for the Ka-band. On the one hand, ridge guides have proven to be an important factor when it comes to waveguide design, due to the advantages they offer in cut-off frequencies. In addition, different improvements are required to achieve good S-Parameters in any of the planes that have limited values. On the other hand, UWB antenna such as All-Metal Vivaldi element has evidence that they are a promising candidate for LEO SatCom applications even as suffering for high cross polarization when scanning off the principal axes. This is the reason why a tradeoff appears in the initial design steps, between the operational frequency bandwidth to cover and the desired cross polarization level and it should be overcome.

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