3^{rd} *URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022*

A Dual-Band Circularly Polarized Bi-Sectoral Waveguide Horn Antenna for High Power LEOP TT&C Systems

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Abstract

In this study, a dual-band circularly polarized bi-sectoral waveguide antenna is proposed, which is used launch and early orbit phases (LEOP) of telemetry, tracking and command (TT&C) applications of satellite systems to almost cover full space together with omni-directional (toroidal) antennas. The structure consists of four parts (pyramidal horn antennas) each having excited by a single inclined slot being cut over circular waveguide. However, because the overall antenna is only fed with a single rectangular waveguide, it works as transceiver (in TX and RX bands simultaneously). The parts belonging to each band have bi-directional patterns being opposite to each other. Therefore, instead of using four separate antennas each being fed by separate rectangular waveguide to cover both directions in dual band (TX and RX bands) in 3D space, one antenna with just one feed is demonstrated as being sufficient for same purpose. For this purpose, an antenna is designed for a Ku-band TT&C application. The results show that the antenna is dual-band over 500 MHz bandwidth around 11.75 GHz (TX) and 13.75 GHz (RX) center frequencies. The antenna has more than 9.5 dBi peak gain in both main lobes and 15 dB return loss at TX band; and has more than 10 dBi peak gain and 10 dB return loss at RX band. Besides, it has less than 3 dB and 3.5 dB axial ratio (AR) values at TX and RX bands within almost 45º and 60º azimuth and elevation beamwidth values, respectively.

1. Introduction

In telemetry, tracking and command (TT&C) applications of satellite system, there should be a continuous communication between space (satellite) segment and earth (ground) segment in time interval between launch of satellite and settlement of satellite into its orbit around earth, which can be described as launch and early orbit phase [1]. Especially for MEO, GEO satellites and deep space applications where the distance of satellite to earth can be long, transmitted power from TT&C systems can be high. For payload operations with transmitted power up to thousands of watts, reflector antennas are generally used. For LEOP operations, transmitter power can be on order of ten watts especially at S, C or even X band [2, 3]; therefore, wire (dipole, helical) antennas, microstrip antennas, or waveguide/aperture type antennas fed by dielectric supported coaxial connectors can be used [4]. For low power applications, there also exist Ku-band TT&C antennas containing microstrip structures, accordingly, dielectric materials [5]. However, Ku-band transmitters for LEOP operations have usually high output power (i.e. more than 100 Watts); therefore, both the antenna structures and their feeds should not contain any dielectric material that they should be full of metal such as waveguide structures.

TT&C antennas used for LEOP purpose should also have the following properties: wide beamwidth in gain pattern (theoretically full 3D coverage) to get a proper minimum level as received power at any aspect angle with respect to earth, wide axial ratio (AR) beamwidth to be independent from any polarization orientation as much as possible. However, a single antenna is not possible to cover all 3D space that multiple antennas are used for widest coverage as possible. One technique is to use and combine uni-directional circularly polarized hemispherical antennas [6]. However, since frequency bandwidth is significantly restricted with axial (AR) performance of complex septum polarizer feed behind choke horn, these antennas are single band antennas operating either at TX or RX band. Besides, since they are uni-directional antennas, two identical hemispherical antennas (one is directed to earth direction, and the other is directed to just opposite direction) should be used for each band, which gives four separate antennas and separate feeds in total. These antennas have wide elevation beamwidth of about 130º-140º (around θ = 0º) being invariant to azimuth angle [1, 6], which corresponds to a coverage of being more than half of all 3D space (about 60% of full coverage). Another method is the combination omnidirectional antennas and directional (wide coverage) antennas. Omnidirectional circularly polarized waveguide (slot) antennas being either fed by one rectangular waveguide (a dual-band antenna [7]) or two rectangular waveguides (an antenna with two single bands [1]) for high power applications at TX and RX bands can be found. For instance, the dual-band study of [7] has elevation beamwidth of about 50º-70º around θ = 90º giving approximately half coverage (50%) at both bands. Directional antennas (wide coverage antennas - WCA) are generally placed in an orientation that its main lobe is along one of the nulls of omnidirectional antenna [1]. However, as being similar to circularly polarized hemispherical antennas, circularly polarized waveguide (or aperture) type directional antennas are also single band and uni-directional. Therefore, four directional antennas with four separate feeds should be again used.

In this study, instead four directional antennas, one antenna with just one rectangular waveguide feed, which is dual-band, circularly polarized and bi-directional, is proposed.

2. The Structure of Designed Antenna

The designed antenna has a structure as depicted in Fig. 1. It has a dual-band rectangular to circular waveguide converter as a common feed for the transceiver antenna, and two bi-directional radiated sections (apertures). The lower and upper sections belong to TX and RX bi-directional horns, respectively; both of which give main lobes along +x and -x directions (axes) in Fig. 1. Each pyramidal horn is excited with one inclined slot being cut over TX or RX circular waveguide to give two orthogonal E-field components inside horns. With the proper flare angles in two principal planes of pyramidal horns, phase difference between orthogonal components is arranged to be 90º at the apertures resulting in circular polarization.

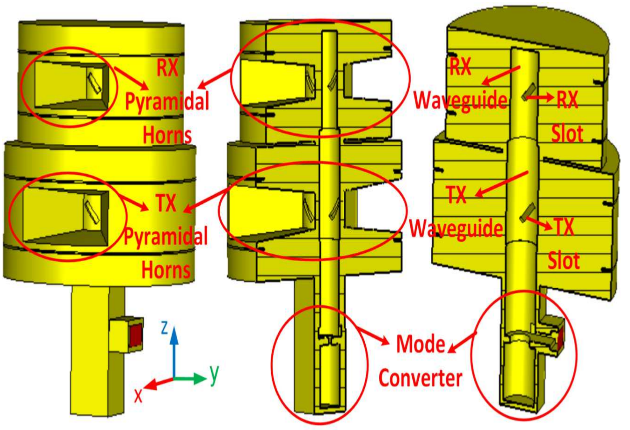

Figure 1. The structure and cut views of designed antenna.

2.1 Dual-Band Rectangular TE_{10} Mode-to-Circular TM_{01} Mode Converter

In multi-sectoral antenna applications, each sector should be excited with same amplitude and phase [8]. Since each sector in the antenna at Fig. 1 is excited by a slot on a circular waveguide, the fields over these slots should be same, which can be obtained with cylindrically symmetric mode of TM_{01} mode [7, 8]. However, since the common feed waveguide of the designed antenna for dual-band operation is rectangular waveguide (WR75 in a Ku-band application) to be compatible with microwave components behind antenna in satellite channel (space segment), a mode converter to convert rectangular dominant TE_{10} mode into circular TM_{01} mode and to suppress circular dominant TE_{11} mode inside the circular waveguide. The mode converter given in Fig. 2, whose basic design details can be found in [7], is actually modified version of mode converter in [7]. As compared to that converter, the proposed structure gives a simpler structure in terms of manufacturing by containing one iris and one cavity section below iris to cancel out circular TE_{11} mode and putting an E-plane step to improve S_{11} values.

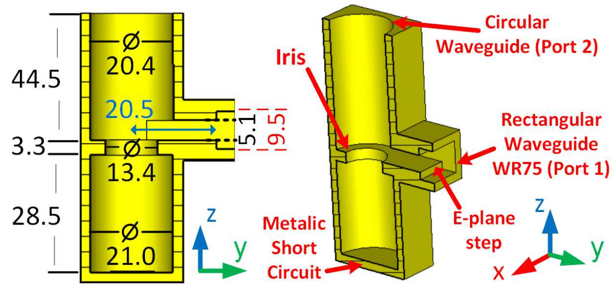

Figure 2. Cut view of rectangular TE_{10} mode to circular TM_{01} mode converter part (feed) of overall antenna.

The dimensions of mode converter are optimized in CST Microwave Studio with PEC material to give more than 15 dB return loss and suppression of TE_{11} and TE_{21} modes at dual-band (11.5-12 GHz for TX band and 13.5-14 GHz for RX band). The corresponding S-parameters are shown in Fig. 3 that the desired specifications are satisfied.

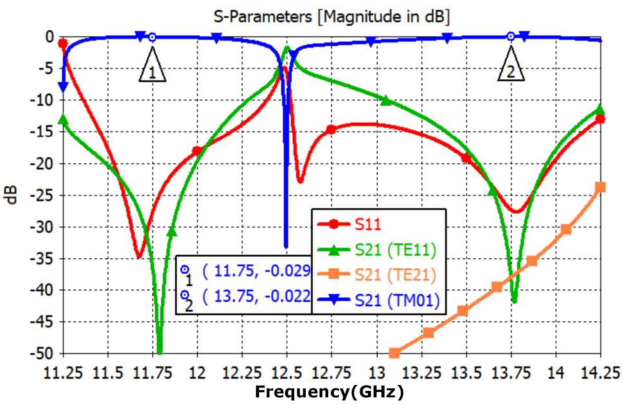

Figure 3. Simulation S-parameters of designed dual-band mode converter given in Fig. 2.

2.2 Dual-Band Bi-Directional Horn Antenna Excited by Slots

The radiating part of proposed antenna contains four pyramidal horns (or two bi-directional horns) each of which is excited with single slot as shown in Fig. 4. TX and RX circular waveguides with diameters of 21.2 mm and 18.2 mm, respectively, are consecutively connected to circular output of mode converter. RX diameter is selected such that TX frequencies are below cutoff of TM_{01} mode at RX waveguide, over which makes TX frequencies highly attenuating. TX diameter is selected such that the cutoff frequency of TE_{21} mode for TX waveguide becomes almost 13.75 GHz, which minimizes undesired RX frequencies passing through TX waveguide and leaking from TX slots.

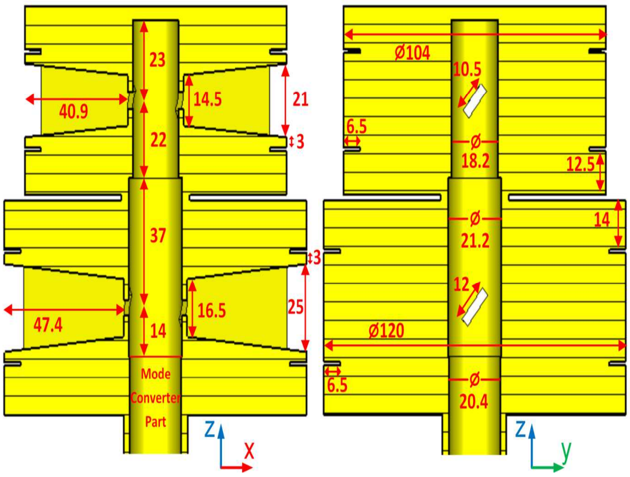

Figure 4. The cut views and dimensions (in mm) of related parameters for bi-sectoral parts of the proposed antenna.

The vertical dimensions inside circular waveguides in Fig. 4 are arranged to maximize the slot impedances and improve S_{11} values over TX and RX bands. The slots' width and length values are 3 mm by 12 mm for TX slots and 3.2 mm by 10.5 mm for RX slots. In order to get circular polarization at the apertures of the horn, slots are placed in an inclined way with respect to z-axis. The selected incline angle of $\theta = +42.5°$ for both TX and RX sections in this study gives right hand circular polarization (RHCP), where $\theta = -42.5°$ can give LHCP. Two orthogonal electric fields inside pyramidal horns/sectoral waveguides propagate with different phase velocities due to different flare angles at azimuth and elevation planes. The flare angle at azimuth plane (xy plane in Fig. 4) is 28.5° for both TX and RX sections. The flare angles for elevation plane can be calculated from height of aperture, height of throat and length of the horns. These flare angles are critically optimized to give 90° phase shift between orthogonal electric fields at the apertures and to obtain sufficient gain and axial ratio (AR) performance within desired azimuth and elevation beamwidth.

The surface currents are efforted to minimize; therefore, AR performances are improved by inserting radial chokes over circular walls extending through the apertures of the horns. The thickness and length values of radial chokes are 1 mm and 6.5 mm for both TX and RX sections.

3. Performance Results

The designed antenna described in Section 2 is optimized in CST Microwave Studio in terms of its dimensions to give sufficient performances in TX & RX bands for return loss, for gain and axial ratio patterns along desired main lobe directions of +x and -x axes, and to reduce the levels of far minor lobes along undesired directions of +y, -y, +z and -z axes at which omnidirectional antenna has its main lobes in LEOP operation. As the initial performance result, S_{11} values for overall antenna is shown in Fig. 5 that they are lower than -15 dB for 11.5 GHz – 12 GHz (TX band) and lower than -10 dB for 13.5 GHz – 14 GHz (RX band).

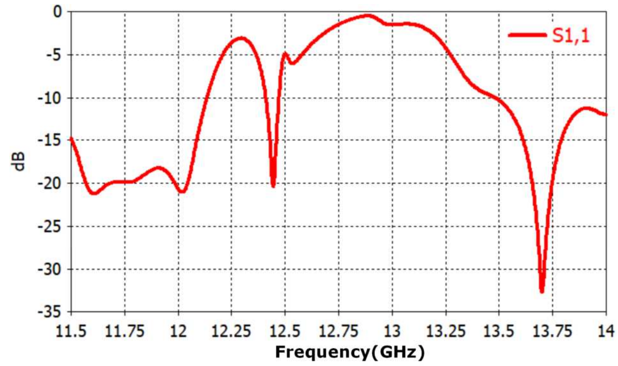

Figure 5. Simulation S-parameters of overall antenna.

As compared to S_{11} values in Fig. 3 for mode converter, while the values at Fig. 5 is similar for TX band (meaning that input impedance of radiation part given in Fig. 4 has good matching), those for RX band worsens (but being still lower than -10 dB).

The gain and AR patterns of antenna are given from Fig. 6 to Fig. 9 at the edge and center frequencies of TX and RX bands. The antenna has more than 9.5 dBi and 10 dBi gain along main lobes ($\theta = 90°$, $\phi = 0°$ and 180°) within TX and RX bands. Besides, the antenna has more than 4 dBi gain within beamwidth of $60° \leq \theta \leq 120°$, $-22.5° \leq \phi \leq 22.5°$ and $157.5° \leq \phi \leq 202.5°$, which covers about 12.5% of full 3D space at dual-band. In the same beam coverage, AR values are found at most 3 dB and 3.5 dB for TX and RX bands.

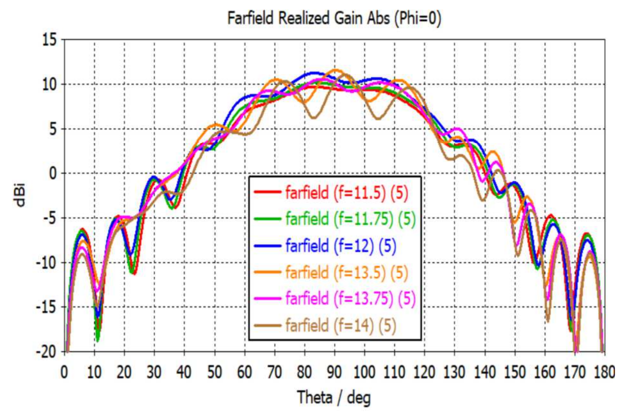

Figure 6. The gain patterns at elevation (xz) plane.

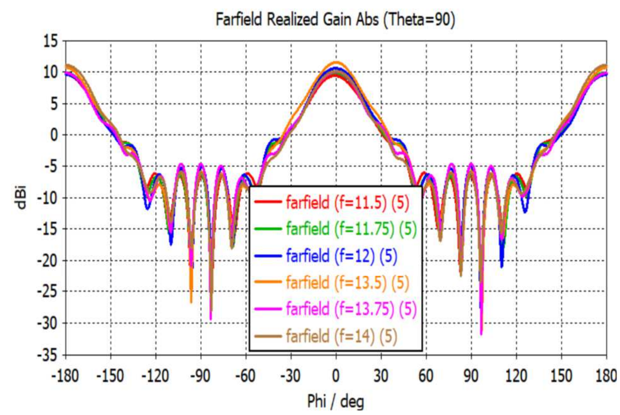

Figure 7. The gain patterns at azimuth (xy) plane.

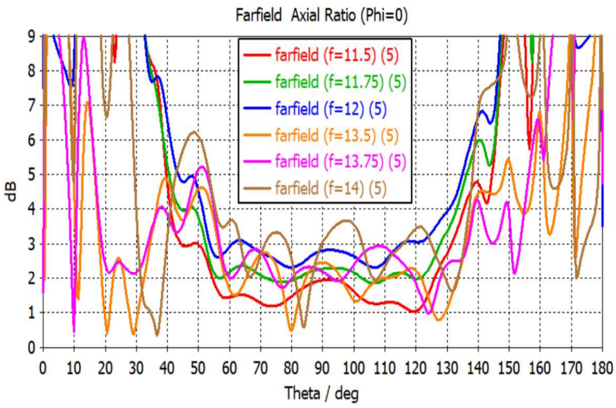

Figure 8. The axial ratio patterns at elevation (xz) plane.

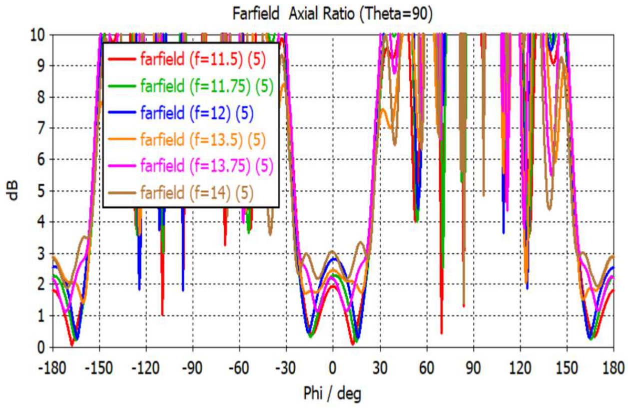

Figure 9. The axial ratio patterns at azimuth (xy) plane.

The antenna is found to effectively suppress radiation along undesired directions that the gain values are less than -5 dBi over $50° \leq \phi \leq 130°$ and $-130° \leq \phi \leq -50°$. When the patterns especially in Fig. 6 are noticed, RX frequencies possess more ripple in gain due to higher leakage radiation as compared to TX frequencies. LEOP WCA given in [1], which is single band and uni-directional, has 12 dBi gain in one main lobe, and more than 7 dBi gain and less than 3 dB AR within $0° \leq \theta \leq 30°$, $0° \leq \phi \leq 360°$, which gives only 6.7% space coverage. Two identical antennas of [1] at each band are needed and generally fed by hybrid coupler for power division and septum polarizer for circular polarization (none of them are needed for proposed antenna in this study), which brings at least 3 dB loss. Therefore, effective gain values are actually 9 dBi along main lobe and at least 4 dBi for $\theta \leq 30°$, which are similar with the proposed dual-band bi-directional antenna.

4. Conclusions

In this study, a dual-band bi-sectoral horn antenna is proposed LEOP TT&C applications of satellite systems. It operates a transceiver antenna for with just one rectangular waveguide feed. The pyramidal horn antennas in TX and RX sections are excited by inclined slots with symmetric circular TM_{01} mode being converted from rectangular TE_{10} mode. Flare angles of azimuth and elevation planes inside horns are arranged to give circularly polarized waves at the apertures and at free space. As a Ku-band demonstration, the antenna gives about 10 dBi gain in both main lobe directions and less than -5 dBi gain in undesired directions at both TX and RX bands. It has sufficient gain and circular polarization performances over 45° and 60° azimuth and elevation beamwidth. Since the structure is fully composed of metal, it is suitable for high RF power applications such as satellite or other wireless communication.

5. Acknowledgements

This work is supported by TUBITAK 1001 programme under the grant no. 119E265.

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