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Omnidirectional and Circularly Polarized Transceiver Antenna for TT&C Communication in Satellite Systems

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Abstract

In this study, the design of an omnidirectional and circularly polarized waveguide antenna used as a transceiver in telemetry/telecommand applications of satellite systems is described. Instead of separate transmitter (TX) and receiver (RX) antennas used in space segment, the proposed antenna can realize transmit and receive operations (TX/RX) simultaneously, which results in the reduction in the number of antennas. The proposed antenna has two sets of inclined slots on circular waveguides with different radii. The below slots operate at TX frequencies around 11.75 GHz, and above slots make an effective radiation at RX frequencies around 14 GHz. In the antenna design, while metallic disks extending away from circular waveguides improve axial ratio performance, a special dual-band rectangular-to-circular waveguide mode converter provides better omnidirectionality. The designed antenna has 10 dB impedance bandwidth more than 150 MHz and 415 MHz at TX and RX frequencies. In azimuth plane, gain variation is lower than 2 dBi, axial ratio is also lower than 1.63 dB at both frequency bands. In elevation plane, minimum gain is found as -5 dBi and axial ratio is below almost 3 dB within 55° beamwidth.

1 Introduction

Satellite communication systems are investigated by dividing into two main parts as ground segment and space segment. The data link between these segments must be continuous. To provide the uninterrupted communication link between the space segment and the ground segment of the satellite systems, special antennas, which are called as TT&C (Telemetry, Tracking, and Command) antennas, are used. Incoming signal power level, especially until the satellite reaches the desired altitude with proper trajectory, is fluctuating. The constant incoming power level is ensured by using non-directional and circularly polarized antennas, which can prevent the incoming signal level fluctuations, as TT&C antennas in satellite systems [1].

Space segments of the satellite communication systems are about 36.000 km away from the Earth. When this distance is considered, level of RF signal power radiated from the antennas should be in hundreds of Watts. Besides, the space segment of the satellite systems exposure high mechanical shocks and vibrations, while they are leaving from the atmosphere. Therefore, waveguide type antennas are frequently preferred in satellite systems due their high-power carrying capacity and mechanical durability.

The power fluctuation in transmission/reception due to aspect angle and polarization variation is generally minimized with two TT&C antenna types. The first type uses hemispherical antennas [2], which are located at top and bottom surfaces of satellite. The second type contains omnidirectional antennas [3] placed perpendicular to each other. For both types, there are separate antennas operating for transmitter (TX) or receiver (RX) frequencies, which gives four antennas in total [1-3]. However, there are no wideband or multiband nondirectional and circularly polarized antennas both covering TX and RX frequencies.

In the study, a dual-band TT&C antenna used as a transceiver antenna is designed at Ku-band for the first time in literature. The antenna has omnidirectional radiation patterns and left-hand circular polarization (LHCP) at both TX (around 11.75 GHz) and RX (around 14 GHz) frequencies. Therefore, the number of TT&C antennas used in space segment can be reduced to only two antennas.

2 Dual Band TE_{10}-TM_{01} Mode Converter for Transceiver Structure

RF signals are carried with rectangular waveguides in the space segment of satellite systems. WR75 is a standard dimension rectangular waveguide used in Ku-Band. To ensure the designed transceiver antenna is compatible with satellite subsystems, the mechanical input interface of the antenna is determined as WR75. Although mechanical interface of transceiver structure is WR75 rectangular waveguide, the antenna slots in the antenna design are placed on a circular waveguide symmetrically to provide omnidirectional radiation pattern. Rotationally symmetric placement of antenna slots on circular waveguide is not enough to obtain an omnidirectional radiation pattern that antenna slots should be fed by a rotationally symmetrical propagation mode inside circular waveguide, which is TM_{01} mode. Therefore, a rectangular TE_{10} to circular TM_{01} mode converter, which also provides rectangular WR75 waveguide to circular waveguide transition, is designed to allow the propagation of TM_{01} mode while suppressing asymmetric modes such as TE_{11} and TE_{21}.

For single band (either TX or RX) operation, the structure for the previously designed mode converter is given in Figure 1 [3]. Here, there are two design parameters, which

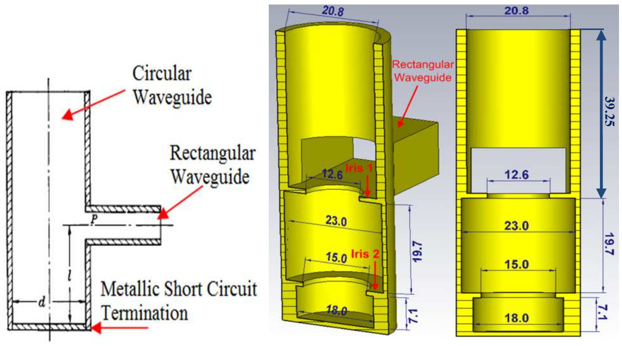

Figure 1. The half cross-section views of rectangular TE_{10} to circular TM_{01} mode converters. Single band (left) [3], dual-band (right, dimensions in mm) [4].

are the distance between point P and bottom metal (l), and the diameter of the circular waveguide (d). The former parameter should be three-quarters of guided wavelength of the fundamental TE_{11} mode ($0.75\lambda_{g,TE11}$) to suppress this mode and other undesired modes [5]. The selection of $l = 0.75\lambda_{g,TE11}$ also gives $l = 0.5\lambda_{g,TM01}$ for desired TM_{01} mode when d is also selected as $0.5\lambda_{g,TM01}$, which provides the propagation of TM_{01} mode along circular waveguide within a wider bandwidth.

Although the given structure, which can be also considered as single-section cavity, provides enough performance for single band operation, dual-band (transceiver) operation cannot be met by just arranging the values of d and l. In order to cover both operating frequencies, a dual-band mode converter as given in right part of Figure 1 is proposed. It contains a two-section cavity with different diameters and additional irises. The dimensions of cavity sections are determined with similar approach to the single band design. Total electrical path length below rectangular waveguide to bottom wall should be odd integer multiple of quarter wavelength of TE_{11} mode both at TX and RX frequencies. This causes high impedance transformation to point P from short impedance of bottom metal for TE_{11} mode, which blocks propagation of TE_{11} mode inside the circular waveguide. This total path length should also correspond to integer multiple of half wavelength of TM_{01} mode at both bands for efficient transmission of this mode. At section boundaries additional irises with 1 mm thickness are placed. The irises increase flexibility in the designed parameters by bringing the reactance effect in the circuit equivalent model. Additional irises are found to improve suppression of TE_{11} mode while reducing return loss [4].

In order to be consistent with single band designs, TX and RX frequencies are also selected as 11.75 GHz and 14 GHz, respectively, for dual-band (transceiver) structure. The dimensions of dual-band design are optimized by CST MWS. The diameters of the cavities are obtained as 23 mm and 18 mm being very close to diameters in previous single band designs [1, 3]. The length of the cavities are 19.7 mm and 7.1 mm respectively. The diameter of the circular waveguide, which is above the rectangular waveguide is optimized as 20.8 mm. This diameter allows TM_{01} mode propagation for both 11.75 GHz and 14 GHz frequencies since cutoff frequency for TM_{01} mode is 11 GHz. Besides, cutoff frequency of second higher order mode (TE_{21} mode), which is another asymmetrical propagation mode, is 14.02 GHz. Therefore, the selection of a diameter of 20.8 mm makes TE_{21} mode attenuated inside the circular waveguide.

The simulation results of the scattering parameters for the given dual-band rectangular TE_{10} mode to circular TM_{01} mode converter are shown in Figure 2. Return loss of the mode converter is higher than 10 dB, and the suppression of undesired circular modes of TE_{11} and TE_{21} are higher than 15 dB at transmitter (11.75 – 12.14 GHz) and receiver (13.67 – 14 GHz) frequency bands. Transmission loss of symmetrical propagation mode inside circular waveguide TM_{01} is also less than 0.5 dB within the same bands.

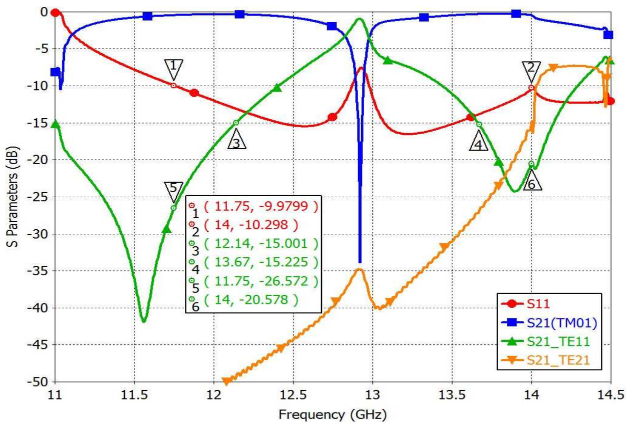

Figure 2. Reflection (S_{11}) and transmission (S_{21}) coefficients of the dual-band rectangular TE_{10} to circular TM_{01} mode converter in Figure 1.

3 The Design of Transceiver Antenna

In the overall design, the dual-band (transceiver) mode converter feeds the transceiver antenna as depicted in Figure 3. The transceiver antenna consists of two slotted antenna arrays where lower and upper slots operate at around 11.75 GHz and 14 GHz. Each array has 8 identical elements placed symmetrically on the circular waveguides with different diameters (23 mm for lower/TX waveguide and 19.6 mm for upper/RX waveguide). The smaller diameter of 19.6 mm on waveguide with RX slotted antenna array corresponds to cutoff frequencies, which are very close to 11.75 GHz for TM_{01} mode. Therefore, this mode significantly attenuates until it reaches upper slotted antenna array at TX operating frequency that the radiation for TX frequencies is mainly from lower slots. For 14 GHz, radiation is desired to be mainly on upper slots; however, since the diameter of 23 mm on TX waveguide allows propagation of TM_{01} mode at 14 GHz, there is a leakage radiation from lower slots, which should be minimized.

The lengths of the antenna slots are adjusted as almost half of free-space wavelength ($\lambda_0/2$) respectively at TX and RX frequencies. To reduce reflections, the width of the antenna slots is chosen much smaller than its length ($\lambda_0/20$) [6].

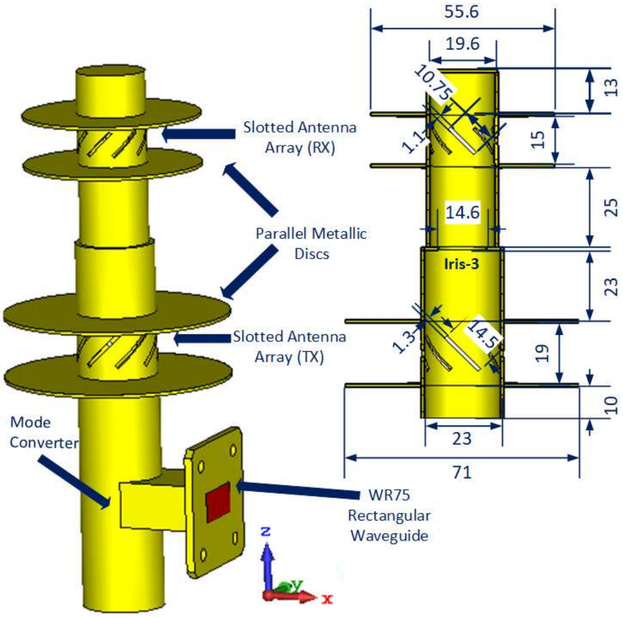

Figure 3. Overall transceiver antenna structure (left), and half cross-section view of antenna part (right), units in mm.

As given in Figure 3, the antenna slots are cut 45˚ slanted way, and two parallel circular disks with 1 mm thickness values are placed above and below of slotted antenna arrays to provide circular polarization. Without these circular disks, 45˚ slant cut of slots can only give 45˚ slant linear polarization for the radiated fields. The axial ratio of the antenna can be arranged with dimensions of the parallel disks. EM waves between these parallel metallic circular disks propagate within radial waveguide. The vertically polarized component propagates with TEM mode having free-space phase constant (β_{TEM}). Horizontal component of EM wave propagates in TE_1 mode [7] with guided phase constant (β_{TE1}). In order to provide circular polarization, the equation (1) should be satisfied.

$$(\beta_{TEM} - \beta_{TE1}) \times \left(r - \frac{d}{2}\right) = \frac{\pi}{2} \qquad (1)$$

where r is theradius of the circular metallic discs extending away, and d is the outer diameter of circular waveguide [3]. Due to tilt directions of slot elements, the polarization of the antenna is LHCP at both TX and RX frequencies.

Slotted antenna arrays must be fed by only symmetrical TM_{01} propagation mode for omnidirectional radiation pattern. Other propagation modes bring disturbance effect on omnidirectionality. Dual-band rectangular TE_{10} mode to circular TM_{01} mode converter provides suppression asymmetrical modes TE_{11} and TE_{21} while allowing the propagation of TM_{01} mode in both TX and RX frequencies. However, the dimensions on the antenna part (especially vertical length values given in the right part of Figure 3) are also crucial to maximize the radiation of desired frequency and mode from desired slots and reduce the radiation of interference modes at undesired frequency. An iris (Iris 3), in addition to Iris 1 and Iris 2 in mode converter, is also placed between TX and RX circular waveguides to provide better return loss/matching at TX/RX frequencies.

The distance between upper wall (short) and upper slot is selected as nearly $0.5\lambda_{g,TM01}$ at 14 GHz, which also corresponds to almost $0.75\lambda_{g,TE11}$ electrical length. Therefore, short circuit impedance on the upper wall is transformed to position of RX slots as very low impedance for TM_{01} mode and very high impedance for TE_{11} mode, which are added to antenna impedance in series. This causes maximum radiation from RX slots for desired TM_{01} mode and minimum radiation for undesired TE_{11} mode. The distance between upper and lower slots is arranged to have an electrical path length of $1.25\lambda_g$ for TM_{01} mode and about $2\lambda_g$ for TE_{11} mode. Therefore, high impedance for TE_{11} mode at upper slot position is again transformed as high impedance at TX slots, which again makes low radiation at TX slots for TM_{01} mode of 14 GHz. On the other hand, low impedance for TM_{01} mode is transformed as high impedance at TX slots, which minimizes the radiation of this mode at 14 GHz.

For 11.75 GHz, since cutoff frequency for TM_{01} mode inside RX circular waveguide is about 11.72 GHz, which is very close to TX frequency, the guided wavelength is very large. Thus, the impedance transformed to Iris 3 position from upper wall is low. The electrical length between Iris 3 and TX slots is approximately $0.5\lambda_{g,TM01}$ at 11.75 GHz. This makes carrying of low impedance at Iris 3 position to TX slots' position, which is added in series with TX slots' impedance and maximizes the radiation from these slots. Mode converter connected below antenna in Figure 3 has circular waveguide diameter of 20.8 mm. If diameter of TX circular waveguide is also taken as 20.8 mm, $\lambda_{g,TM01}$ at 11.75 GHz becomes very large. (height of 23 mm in Figure 3 becomes almost 48 mm). This makes considerable increase in the height of overall structure. Vertical path length from top wall to TX slots is also arranged to transform short impedance at top wall to high impedance at TX slots' level for asymmetric TE_{11} mode.

Theoretical length values given in preceding paragraphs are used as initial values of the parameters, and these parameters are again optimized with CST MWS. Final dimensions of the antenna part of proposed transceiver design are given in right part of Figure 3. The simulation results of designed transceiver structure are given in Figure 4-6. 10 dB impedance/return loss bandwidth are 152 MHz (11.749 – 11.901 GHz) and 414 MHz (13.825 – 14.241 GHz) for TX and RX operations as given in Figure 4. The LHCP radiation patterns at 11.75 and 14 GHz are given Figure 5. In azimuth plane (θ = 90°), patterns show good omnidirectional characteristics that gain variation is lower than 2 dBi. In elevation plane (ϕ = 0°), minimum -5 dBi gain is found between 45° and 120°, where this minimum gain value is generally accepted in TT&C satellite systems. The axial ratio (AR) performance of the antenna is given in Figure 6 that AR values in azimuth plane are below 1.63 dB and 0.89 dB at 11.75 GHz and 14 GHz, respectively. In elevation plane, AR values are under almost 3 dB within 55° beamwidth (65° – 120°). Higher fluctuation observed in the elevation plane for 14 GHz as compared to 11.75 GHz is due to leakage radiation of 14 GHz from TX slots.

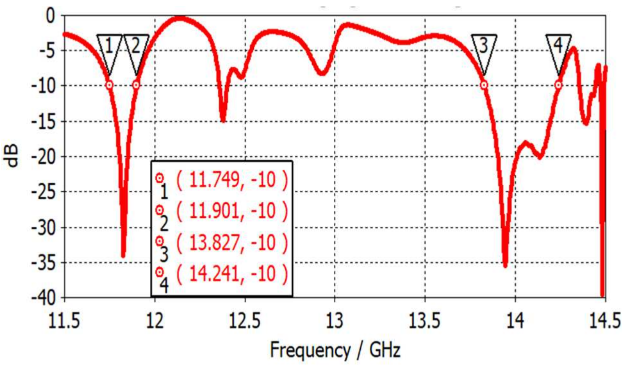

Figure 4. Reflection loss (S_{11}) of transceiver antenna.

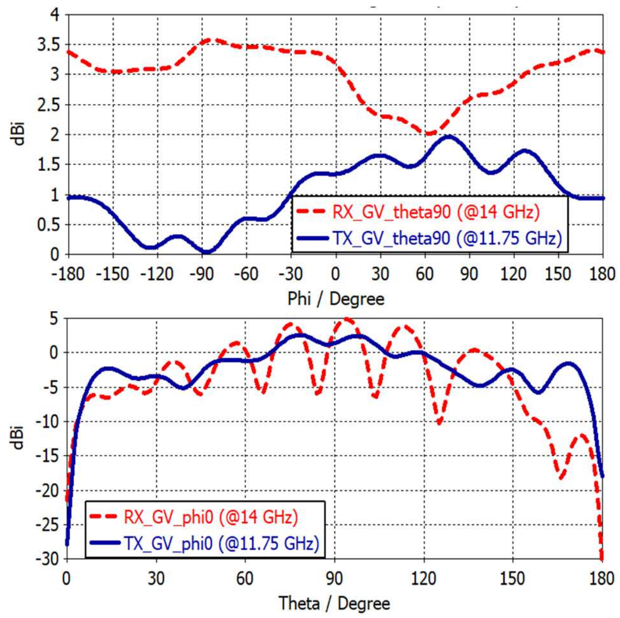

Figure 5. LHCP gain patterns in azimuth (θ = 90°) and elevation (ϕ = 0°) planes at 11.75 GHz and 14 GHz.

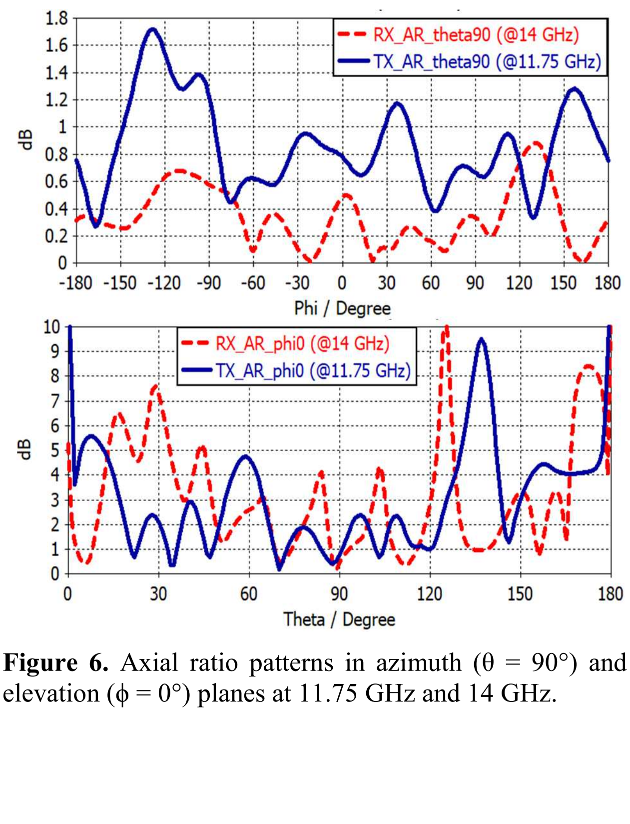

Figure 6. Axial ratio patterns in azimuth (θ = 90°) and elevation (ϕ = 0°) planes at 11.75 GHz and 14 GHz.

5 Conclusions

In this study, an omnidirectional and circularly polarized TT&C antenna, which operates at dual TX/RX frequencies simultaneously, is designed and simulated. The structure contains a dual-band rectangular-to circular waveguide transition to feed antenna slots on circular waveguides with symmetric TM_{01} mode. Two sets of slanted slots, which are cut symmetrically on these waveguides, and radially extending metallic disks around give omnidirectional pattern and circular polarization. 10 dB impedance bandwidths are found as 152 MHz (1.3%) and 414 MHz (3%) for TX (11.75 GHz) and RX (14 GHz) frequencies, respectively. In azimuth plane, the axial ratio is lower than 1.63 dB and gain variation of the antenna is under 2 dBi for both TX/RX frequencies. Minimum -5 dBi gain and 3 dB AR are found within 55° beamwidth in elevation plane.

6 Acknowledgements

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