THE VARIATIONS OF OMNIDIRECTIONAL CIRCULARLY POLARIZED ANTENNAS FOR SATELLITE TELEMETRY/TELECOMMAND APPLICATIONS

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Abstract: *In this paper, the design, production and results of different types of omnidirectional and circularly polarized antennas for satellite communication applications such as telemetry or telecommand, are explained. These antennas consist of identical inclined slots placed on a circular waveguide and two radially outward parallel cylindrical plates in order to provide circular polarization. The feeding of the antenna is provided by a special transition structure between rectangular waveguide to circular waveguide. The first type of antenna contains eight identical slots on the circular waveguide, which gives about 3 percent frequency (impedance) bandwidth for 10 dB return loss. This antenna provides gain variation of about 0.7 dBi and axial ratio lower than 1 dB in the azimuth plane at the center frequency. The second type, which is designed to enhance the frequency bandwidth, includes nonidentical slots on the circular waveguide where the length of four among eight slots is reduced. This enhanced version increases impedance bandwidth to 5.8 percent. The gain variation and axial ratio performances of the second type antenna are slightly lower as compared to first version at the expense of improvement in bandwidth; however, the results of both types are still satisfactory for satellite applications.*
Keywords: *Slotted Array, Circular Polarization, Omnidirectional Antenna, Satellite Communication*

1. Introduction

In satellite communication, instantaneous aspect angle of satellite with respect to earth (ground station) cannot be exactly known at the time interval between launch of satellite and settlement of satellite to its desired orbit. The communication between ground station and satellite during this critical time interval is provided via some special antennas, which are usually defined as Telemetry and TeleCommand (TTC) antennas. It is expected that these antennas should have non-directional radiation pattern in order to transmit and receive electromagnetic waves from any direction [1]. Theoretically, non-directional radiation pattern is known as isotropic radiation pattern; but, isotropic antennas are practically not available. For practical consideration, the almost full space coverage is usually satisfied with the combination of two identical omnidirectional antennas [1-6], which are placed perpendicular to each other on satellite platform, or using two identical hemispherical antennas [7-10], where one of them is placed top platform and the other is placed to bottom platform of the satellite.

One of the most important reasons of power loss in satellite communication is the polarization mismatch. When the antennas on the satellites have circular polarization, the linearly polarized incoming/outgoing waves can be received/transmitted in any orientation angle without any significant power changes [11]. The high gain antennas used in the main satellite communication via transponders or other equipments have generally narrow conical beamwidth, and achieving circular polarization within this narrow beamwidth can be sufficient for these antennas [12]. However, the antennas used in TTC communication should give circular polarization in a much wider beamwidth. In this way, the receiving or transmitting signal levels do not decrease significantly due to polarization loss for random aspect angles of the satellite in the duration where satellite is launched and settled to its orbit.

In this study, two variants of omnidirectional antennas (narrowband and wideband) having circular polarizations over wide angle coverage are proposed for Telemetry/Telecommand applications in satellite communication. The antenna structures mentioned in this study contain a set of inclined slotted array. The slots are curved on the cylindrical waveguides and are oriented to have circular symmetry in order to provide radiation characteristics close to that of an omnidirectional one as much as possible.

One other important issue to be noticed in the design to provide omnidirectional (or low gain variation) is that the

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slots should have not only physical circular symmetry on the circular waveguide but also the fields on the slots should have circular symmetry. The dominant mode on a standard waveguide contains the fields of TE_{11} mode. However, this mode has nonsymmetrical fields, and high gain variations are observed both in azimuth and elevation planes when the slots on the circular waveguide are excited with TE_{11} mode as demonstrated in [13]. The mode providing this circular symmetry is the TM_{01} mode inside a circular waveguide or TEM mode in a coaxial line. Therefore, the feed of these antennas should be done properly to form only the fields of desired mode inside the waveguide. Although the direct feeding of circular waveguide with TM_{01} mode [3, 14] or feed with TEM mode [4, 15] is possible, it is generally employed by inserting the inner conductor (probe) of a coaxial line into circular outer cylinder or using this probe as a feed antenna. For this purpose, the antennas using these feeding mechanisms should be connected the components behind the antennas in satellite communication channel, which are generally waveguide components, with the coaxial (SMA) cables. However, the power level carried to the antennas can be order of a few hundred Watts especially in the telemetry applications where the antennas operate for transmitter purpose. Therefore, the feed of antennas with coaxial cables are not preferred in the applications of high power satellite communication. Consequently, the rectangular waveguides are generally used to connect the antennas and other waveguide components. In this study, a transition between rectangular waveguide and circular waveguide, which is used in the proposed antenna, is considered. This transition is provided by a simple rectangular-to-circular waveguide transition. Here, the dominant TE_{10} dominant mode of rectangular waveguide is converted to non-dominant and symmetric TM_{01} mode of circular waveguide by suppressing the effect of the dominant TE_{11} mode and the other higher order modes of the circular waveguide as possible.

After the sufficient symmetries both in the geometry and the fields are obtained, the circular polarization is formed with a simple method described as follows. The inclined slots in circular waveguide are put in the same slanted way (45 degrees) to obtain desired circular polarization. Then, two surrounding parallel metallic disks, which are radially away from the circular waveguide, are added. The radii of these disks are arranged to give sufficiently low axial ratio and good circular polarization. In order to achieve circular polarization, the other relevant studies in literature are generally used septum polarizers [7-10], 90° hybrid phase shifter [12, 16], or slots/strips on dielectric resonator antennas (DRA) [17-19], all of which have certain drawbacks to proposed circular polarization mechanism especially in high power satellite communication applications. The septum polarizers used in waveguide-based hemispherical antenna for the purpose wide angle coverage in azimuth and elevation [7-10] are bulky waveguide components, and need to be designed carefully bringing an increase in the total volume and complexity of the antenna design. On the other hand, the designs with 90° hybrid phase shifters or slots/strips on dielectric resonator antennas [12, 16-19], used to generate circular polarization, contain dielectric materials either in the feeding or antenna part of the overall structure. Although the usage of dielectric materials usually increases the bandwidth, it has an adverse effect on the radiation efficiency. Besides, dielectric materials in any part of the antenna are not preferred in satellite communication applications with high power levels due to mechanical and thermal instability problems. This is because the power levels dissipated on the dielectric materials can be severe when high power levels at higher frequencies are considered. Most of the mentioned studies with dielectric materials are realized at relatively lower frequencies such that the radiation efficiency will be worse and the dissipated power will be higher at the frequencies performed for satellite communication such as Ku band.

The antennas proposed in this study have two different versions, where the first one possesses better omnidirectionality and axial ratio performances but narrow frequency bandwidth, and the second one has wider bandwidth but lower omnidirectional and axial ratio performances. Therefore, the first version can be used in the satellite telemetry/telecommand applications in which omnidirectionality and axial ratio requirements are stricter than the frequency bandwidth requirement, and the second version is useful when wide bandwidth is required. The first version uses eight identical slots on the circular waveguide, which results in a resonance in one frequency. On the other, the second version uses four slots exactly same with the first version, and other four slots have reduced length, which results in additional resonance at another frequency to the one in first version. Since the first version contains more identical slot elements at a specific frequency, the variation in gain (omnidirectionality) and axial ratio performances are better than the second version. On the other, the second version covers slots resonating at two different frequencies. Therefore, the second version can be considered as a multi-band antenna structure. However, since the slots with reduced length have slightly smaller values than the original slots, two different resonant frequencies are so close to each other, which makes the second version wideband instead of multi-band.

The employed antennas are realized for Ku-band telemetry and telecommand applications at 11.75 GHz transmitter frequency and 14 GHz receiver frequency, respectively. The frequency bandwidths for 10 dB return loss are found to be approximately 3% and 5.8%, respectively, for first and second versions. The gain variation for the first version is found to be about 0.7 dBi in the overall azimuth plane where it is increased to about 1.6 dBi for the second version. The maximum axial ratio values in the azimuth plane are obtained as 1 dB and 1.6 dB for the first and second types, respectively, and it is below 3 dB within 65 degrees beamwidth in elevation plane. Thus, both antennas have satisfactory performances over the azimuth and 65 degrees beamwidth elevation planes.

The main advantages of the proposed structure over the similar studies in literature can be summarized as follows.

i) consisting of only metallic waveguides, no dielectric materials in any part (feed or antenna parts). Better radiation efficiency, lower power dissipation and higher mechanical robustness than the studies containing dielectric materials [4, 6, 12, 16-19]. More suitable for high power satellite communication applications.
ii) compact, no usage of a complex and bulky polarizer or transition component such as septum polarizer [7-10] to get circular polarization.
iii) better performances especially in frequency bandwidth, gain variation and axial ratio as compared to other similar studies containing no dielectric material or septum polarizer [2, 3].

2. The Design of Rectangular-to-Circular Waveguide Transition

The transition structure, which is employed for mode conversion and rectangular-to-circular transition, is given in Figure 1 [20]. In order to obtain omnidirectional radiation pattern, antenna slots are placed on a circular waveguide as symmetrical. Therefore, the antenna slots on circular waveguide should be fed with only symmetrical mode TM_{01} of the circular waveguide. However, the fundamental mode inside circular waveguide is TE_{11}, which is a non-symmetrical mode. For this purpose, a rectangular-to-circular waveguide transition structure is designed to get a transition between two waveguides and mode conversion between TE_{10} mode of rectangular waveguide and TM_{01} mode of the circular waveguide. Here, the fundamental mode TE_{11} and second order higher mode TM_{21}, which are non-dominant modes inside circular waveguide, must be suppressed while mode conversion is realized.

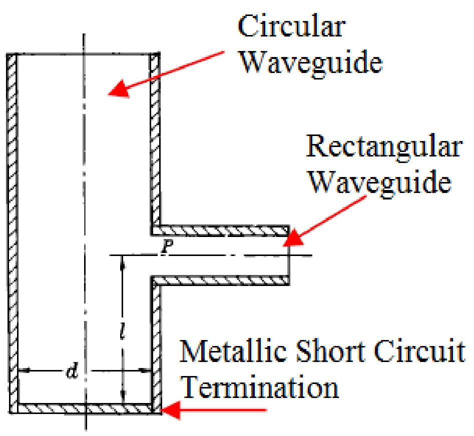


Figure 1. Rectangular-to-circular waveguide structure [20].

The feed rectangular waveguide of the transition structure, so the antenna structure, is selected as WR75 standard rectangular waveguide to be compatible with most of the Ku-band satellite communication applications. By considering the transition structure given in Figure 1, there are crucial two parameters needed to be optimized: the diameter of circular waveguide " d ", and the distance between point P and metallic short circuit termination at the end of the circular waveguide " l ". The diameter " d " should be selected as about half of the guided wavelength of symmetrical mode TM_{01} ($d = \lambda_{g,TM01}/2$), which can be expressed mathematically as [21],

$$\beta = \sqrt{k^2 - \left(\frac{4.81}{d}\right)^2} = \sqrt{(2\pi f)^2 \mu_o \varepsilon_o - \left(\frac{4.81}{d}\right)^2} = \frac{2\pi}{\lambda_{g,TM01}} = \frac{\pi}{d} \quad (1)$$

where $k = 2\pi f / c$ is number of waves. From (1), " d " is evaluated as 23.3 mm and 19.6 mm respectively for transmitter center frequency of 11.75 GHz and receiver center frequency of 14 GHz in the considered designs.

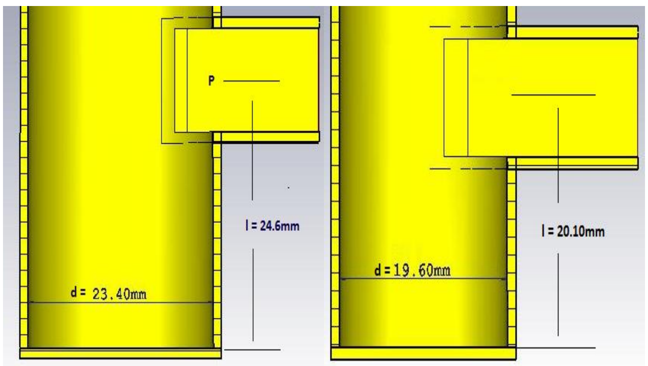
As shown in Figure 1, the bottom side of the circular waveguide is terminated with a short circuit. The " l " distance between short and point P, should be selected as odd integer multiplies of the quarter of the guided wavelength of the dominant TE_{11}. The reason behind this selection is that the short circuit impedance at the bottom of the waveguide is transformed to very large impedance at point P for the dominant TE_{11} mode. Thus, a high reflection occurs for this mode, which provides sufficient suppression. Among the possible selections of the distance " l ", the distance of $l = 3\lambda_{g,TE11}/4$ is more effective for the transmission of the desired TM_{01} in a wider bandwidth [20]

$$l = \frac{3\lambda_{g,TE11}}{4} = \frac{6\pi}{4\sqrt{k^2 - \left(\frac{3.68}{d}\right)^2}} = \frac{6\pi}{4\sqrt{(2\pi f)^2 \mu_o \varepsilon_o - \left(\frac{3.68}{d}\right)^2}} \quad (2)$$

From (2), the distance " l " is found as about 25 mm and 20.9 mm for transmitter frequency of 11.75 GHz and receiver frequency of 14 GHz, respectively.

The transition structure with the dimensions, which are theoretically calculated by using (1) and (2), are simulated and optimized by using CST Microwave Studio 2016. The calculated " d " and " l " values are used as initial values of optimization. In the simulations, it is aimed to have high transmission of TM_{01} and high suppression of TE_{11} and TE_{21} modes. The final values of " d " and " l " parameters are given in Figure 2 where the optimized values are highly close and consistent with the theoretical values.

The magnitudes of reflection and transmission coefficients of critical modes (TE_{11}, TM_{01} and TE_{21}) are shown in Figure 3 for transition structures in Figure 2.



(a) (b)

Figure 2. Final dimensions belonging to designed rectangular-to circular waveguide transition (a) for transmitter structure (b) for receiver structure.

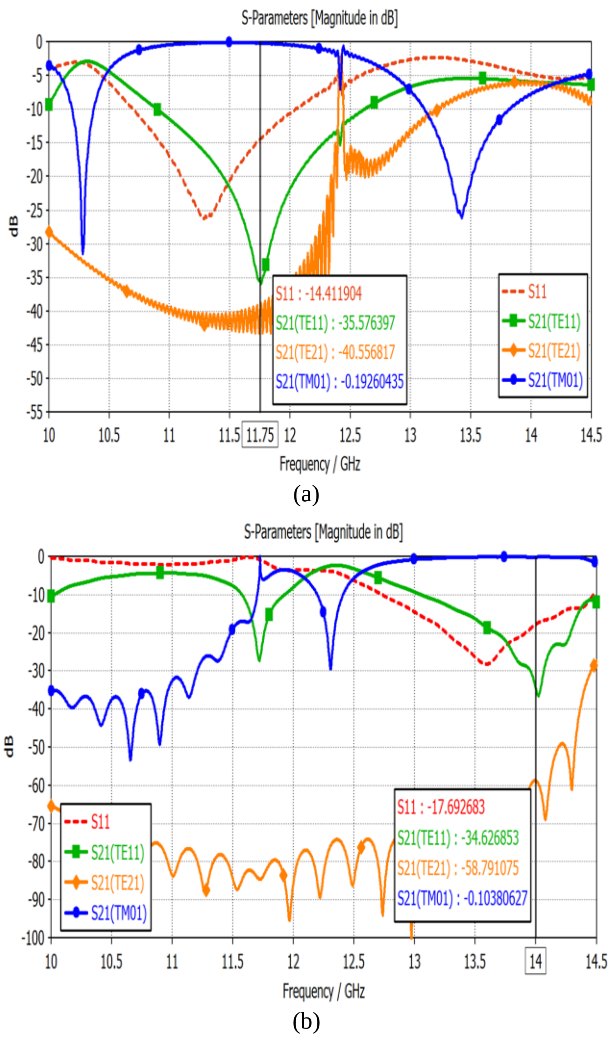


Figure 3. The magnitudes of S-parameters (reflection and transmission coefficients) of the designed transitions for (a) transmitter structure (b) receiver structure.

The desired TM_{01} mode is successfully carried to the circular waveguide from rectangular waveguide such that the transmission of this mode is better than -0.2 dB for the frequency bandwidth of about 500 MHz around the center frequencies in both structures.

3. The Designed Antenna Structure with Better Gain Variation and Axial Ratio Performances: The First Version with Identical Slots

The proposed antenna should have omnidirectional radiation pattern and circular polarization (left hand circular polarization-LHCP or right hand circular polarization-RHCP). In order to obtain omnidirectional radiation pattern, the slotted antenna array in circular waveguide should be fed with the only symmetrical mode of TM_{01}, which is achieved with the transition given in Section 2. The design of the overall antenna is depicted in Figure 4. As it can be seen from the figure, a set of antenna slots, which include identical inclined antenna slots in the first version, are placed on the circumference of the circular waveguide in a circularly symmetrical way. The radiation of the antenna is arisen from these slots. The antenna slots in Figure 4 are -45° inclined, which results in LHCP radiation. The sense (hand) of the polarization can be modified to RHCP by changing of incline of slots to +45°.

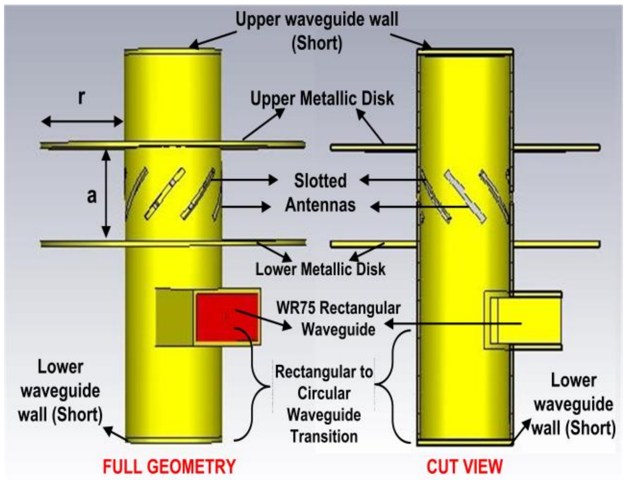


Figure 4. The proposed circularly polarized omnidirectional antenna structure along with cut view for both versions.

The circular waveguide is terminated with short circuit walls from bottom and top ends. The distance between short-circuit termination at the upper end and upper antenna slot set should be adjusted to provide desired radiation resistance. The maximum radiation resistance can be obtained if this distance is chosen as integer multiple of $(\lambda_{g,TM01})/2$ [22]. The length of the antenna slots is directly proportional with the free space wavelength λ_0 under the thin slot assumption such that they should be tuned to about $\lambda_0/2$ at the center frequency. The width of the slots is chosen much shorter than the length of the slots ($w << l$) to reduce reflections. In general, the width of the slots is usually arranged to approximately $\lambda_0/20$.

To obtain circular polarization, two parallel metallic disks for slot set of each circular polarization are placed in the radially outward direction of the circular waveguide as shown in Figure 4. The waves radiating from slots and propagating along radial direction in the metallic disks have vertically polarized component with TEM mode, and horizontally polarized component with TE_1 mode. In order to give 90° phase difference between horizontally and vertically polarized components of the wave, the following equation should be satisfied.

$$\left(\beta_{TEM}-\beta_{TE_1}\right)\times r=\left(\frac{2\pi}{\lambda_0}-\frac{2\pi}{\lambda_{g,TE_1}}\right)\times r=\left(k-\sqrt{k^2-\left(\frac{\pi}{a}\right)^2}\right)\times r=\frac{\pi}{2} \qquad (3)$$

where k is the free space wavenumber, a is vertical distance between two parallel metallic disks of each slot set in Figure 4, and r is the dimension in radially outward direction of the disks.

The antenna of first version with identical slots is designed and demonstrated for a telecommand application at 14 GHz where the antenna on the satellite is in receiver mode. The dimensions of the antenna structure designed in

Figure 4 are initially calculated by using (3) and other mentioned expressions in this section for the center frequency of 14 GHz. Then, the dimensions are tuned by implementing optimization process in CST Microwave Studio 2016. The final dimensions of the proposed antennas for receiver (telecommand) antenna are shown in Figure 5 such that the optimized values are again found to be good agreement with the theoretical expectations.

The designed antenna given in Figure 5, whose corresponding simulation results are also given in [1], is slightly modified for the manufacturing purposes. In the produced antenna, whose simulation view and photograph are shown in Figure 6, all dimensions given in Figure 5 except the thickness of the wall of circular waveguide are kept constant. This thickness, which is 1 mm in the simulation version given in Figure 5, is increased except for the part between the metallic plates as shown in Figure 6. It is the only modification performed to reduce production time and cost.

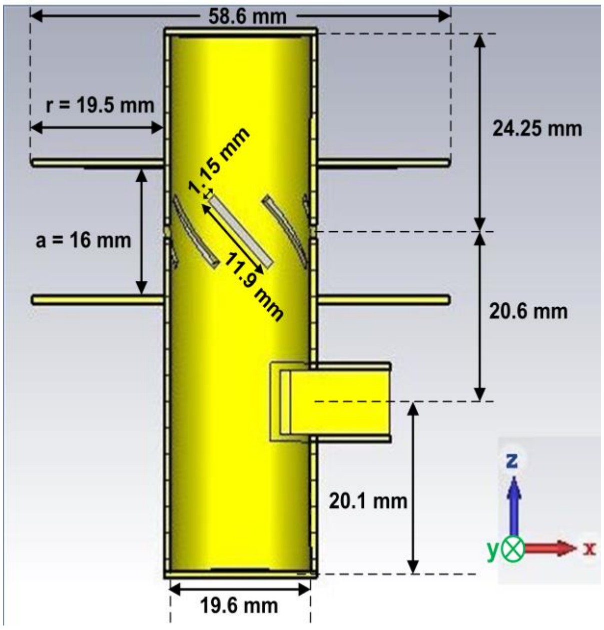


Figure 5. The simulation view of the designed antenna for receiver structure.

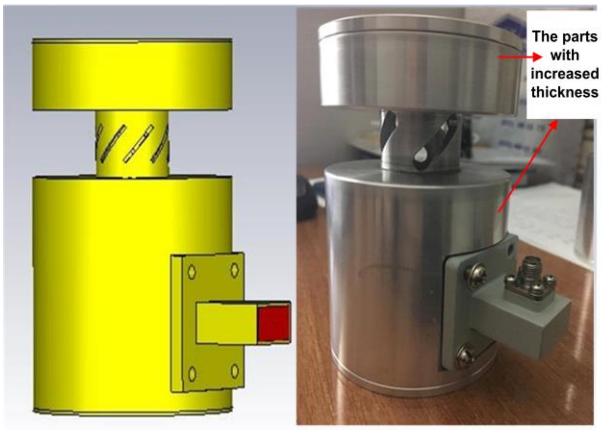


Figure 6. The simulation view and photograph of the manufactured receiver antenna.

The results of reflection coefficients (S_{11} parameter) of the antenna obtained from the simulations of the original antenna in Figure 5, the simulations and measurements of the production modified antenna are expressed in Figure 7. When the results in Figure 7 are investigated, the production modified version does not drastically affect the performance such that both the simulation results for the structures in Figure 5 [1] and Figure 6 have the resonance frequencies of 14 GHz, and the -10 dB impedance bandwidth of 417 MHz (about 3% bandwidth). The measurement results are also consistent with the simulations one such that the frequency having minimum S_{11} in the measurement is approximately 13.96 GHz, which is very close to the desired frequency of 14 GHz. The difference between the measurement and simulation results is probably due to the error in the production process. The obtained frequency (impedance) bandwidth is found to be wider than the mentioned single circularly polarized structures [2, 3] having 1.4% bandwidth at most.

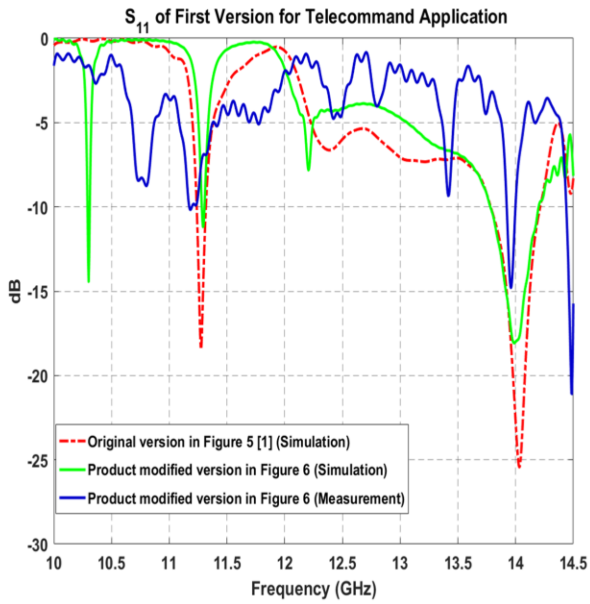
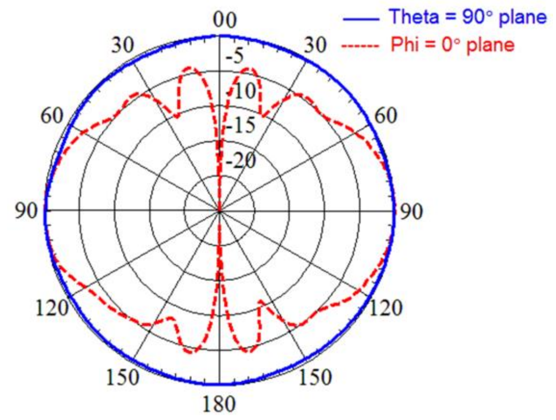


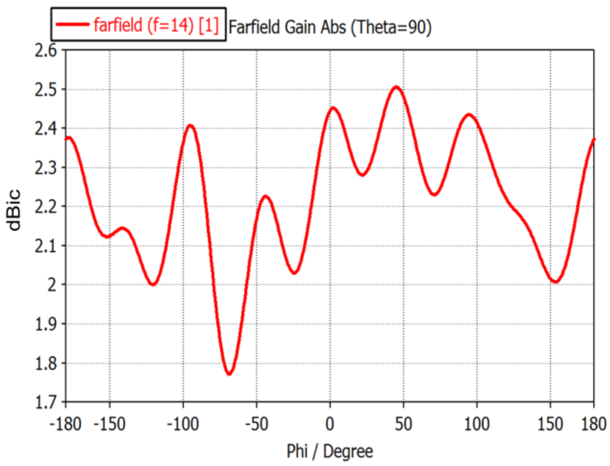
Figure 7. The magnitude of reflection coefficient (S_{11}) of the designed receiver antenna.

The gain and radiation patterns of the designed antenna are also investigated in order to observe the omnidirectional behavior of the antenna. For this purpose, the normalized radiation patterns at both azimuth ($\theta = 90°$) and elevation ($\phi = 0°$) are extracted along with gain patterns in azimuth plane, which are given in Figure 8 for simulation results.

According to the results in Figure 8, the antenna can be said to have almost non-directional in azimuth plane and directional in elevation plane such that it provides omnidirectional radiation pattern properties. The gain variation of the receiver antenna in CST MWS simulations, are lower than 0.7 dBi in azimuth plane, which is sufficiently enough. The manufactured antenna, whose measured gain pattern is depicted in Figure 9, has about 3 dBi gain variation in this plane, which is still acceptable for an omnidirectional antenna.



(a)



(b)

Figure 8. Simulated (a) polar radiation patterns and (b) rectangular gain pattern at the azimuth plane for receiver (telecommand) antenna at 14 GHz.

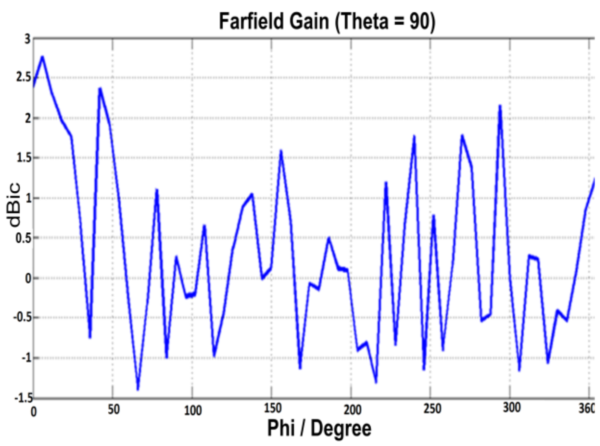
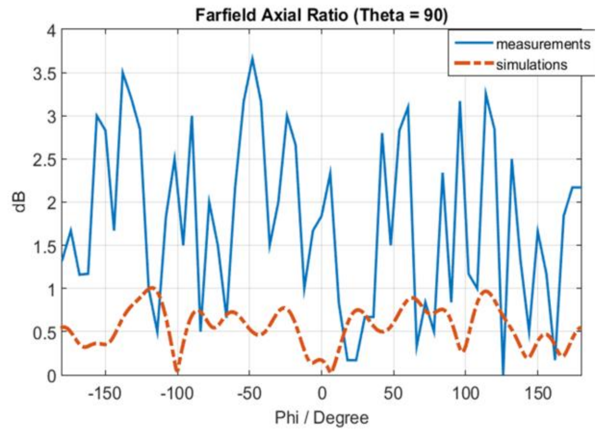
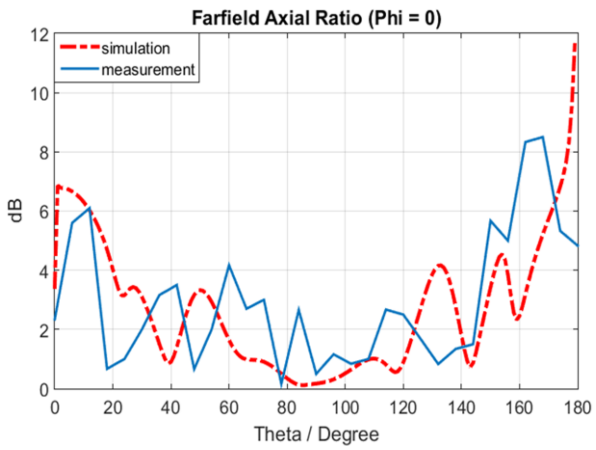


Figure 9. Measured rectangular gain pattern at the azimuth plane for receiver (telecommand) antenna at 14 GHz.

The final investigation is realized about the circular polarization performance of the antenna, which is evaluated with axial ratio values. The axial ratio patterns are given in rectangular form for both azimuth and elevation planes are given in Figure 10. According to the results given in Figure 10(a), the axial ratio in azimuth plane is smaller than about 1 dB and 3 dB in the simulation and measurement results, respectively.



(a)



(b)

Figure 10. The rectangular axial ratio patterns (a) for azimuth plane (b) for elevation plane.

The corresponding results are more similar in elevation plane such that both simulation and measurement results provide maximum of about 3 dB axial ratio within 65 degrees beamwidth. When the threshold value for the axial ratio of circularly is generally considered as 3 dB, the designed antenna can be said to provide good circular polarization performance over the full azimuth plane and 65 degrees beamwidth in the elevation plane both for simulation and measurement results.

4. The Wideband Antenna Structure: The Second Version with Nonidentical Slots

Narrowband antenna design for telecommand antenna is explained in Section 3. Especially, the frequency bandwidth enhancement in the antennas is very important in wideband satellite applications. In this section, the bandwidth enhancement of the antenna introduced in Section 3 (first section) with the usage of nonidentical slots is explained and demonstrated for a telemetry application at 11.75 GHz where the antenna on the satellite is in transmitter mode. For this purpose, first of all, an antenna of first version with eight identical slots is designed by using the procedure explained in Section 3. The optimized dimensions of the simulation view of resulting designed transmitter structure for 11.75 GHz is shown in Figure 11.

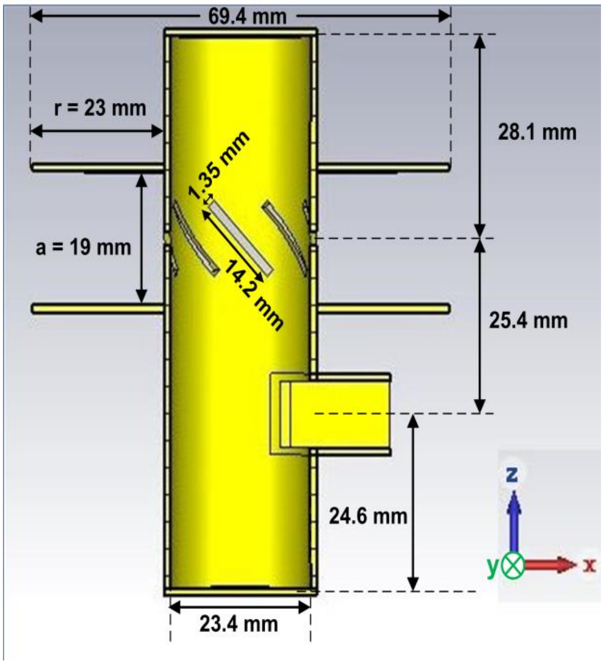


Figure 11. The dimensions of the designed antenna with identical slots for telemetry purpose (transmitter structure).

Here, the length of eight identical slots, which is about 14.2 mm, is optimized to bring a resonance frequency of almost 11.75 GHz. In order to increase bandwidth of the antenna, it is considered to use nonidentical slots where four of eight slots are kept as same with the narrowband design to get a resonance frequency of 11.75 GHz, and the other four slots are slightly shrunk in length to give another but adjacent resonance frequency. For this purpose, the length of four slots is reduced by 1 mm (to 13.2 mm), and the other dimensions of the overall antenna are re-optimized. The resulting S_{11} values of the modified (second version) antenna are given in Figure 12 in addition to the results of the antenna structure given in Figure 8 (first version). The effect of the bandwidth enhancement on the second (modified) version can be clearly observed from the results of Figure 12 such that a resonance frequency of about 12.2 GHz due to smaller slots is added to the resonant frequency of 11.75 GHz due to original slots. The -10 dB frequency bandwidth of the wideband design is increased from 272 MHz to 680 MHz (from 11.62 GHz to 12.30 GHz) such that the bandwidth is increased from 2.32% to 5.8% in terms of percentage.

In Figure 13, the gain variations of the narrow band and wideband versions of the antenna are given in azimuth plane at 11.75 GHz. Maximum gain variation in this plane is about 1.6 dBi, which is greater than 0.67 dBi gain variation in narrow band design. The higher gain variation is expected in wideband design since there are four effective radiating slots in 11.75 GHz at the wideband design instead of eight. Although gain variation increases, 1.6 dBi is still an acceptable variation for omnidirectional property.

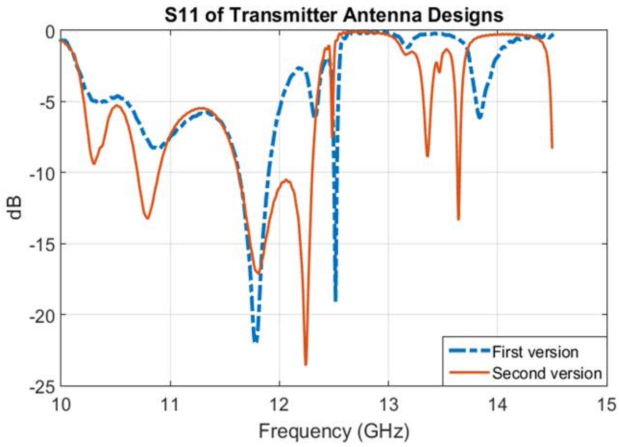


Figure 12. The magnitude of reflection coefficient (S_{11}) of the designed transmitter (telemetry) antennas.

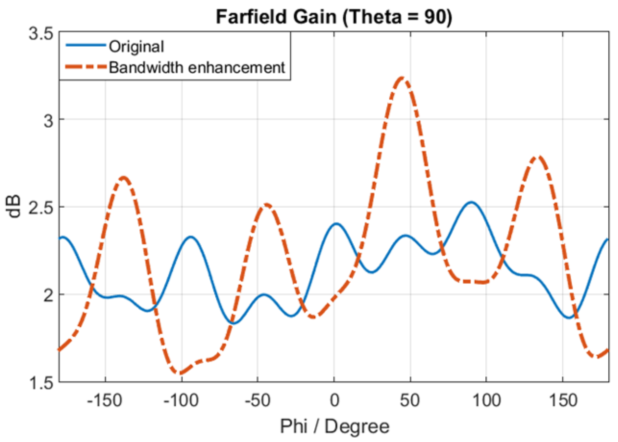


Figure 13. Rectangular radiation patterns of the antennas of first and second versions in azimuth plane at 11.75 GHz.

The axial ratio performance comparison of the antennas of first and second versions 11.75 GHz is given in Figure 14. The value of the axial ratio is less than 2 dB at all directions for both designs where the axial ratio is again higher in wideband antenna design with respect to narrow band antenna design, which is lower than 1.1 dB value. Nevertheless, the axial ratio of the wideband antenna is still lower than standard value of 3 dB in azimuth plane, which is enough for circular polarization requirements practically.

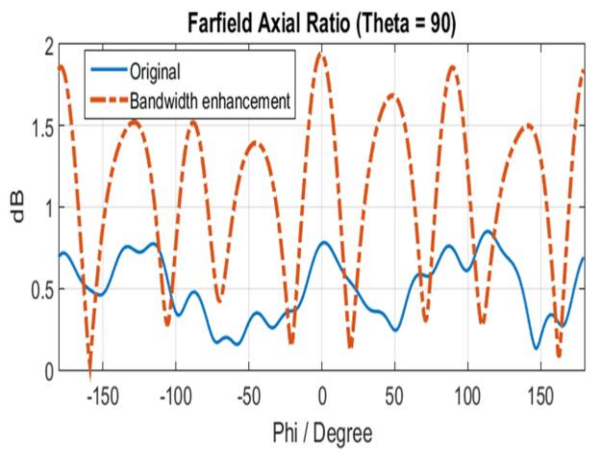
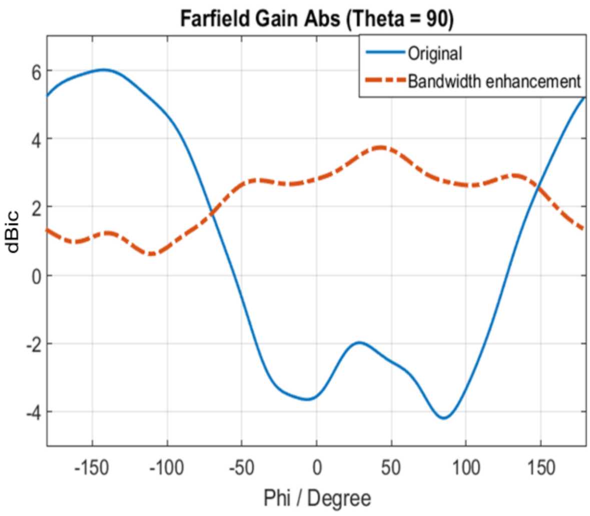
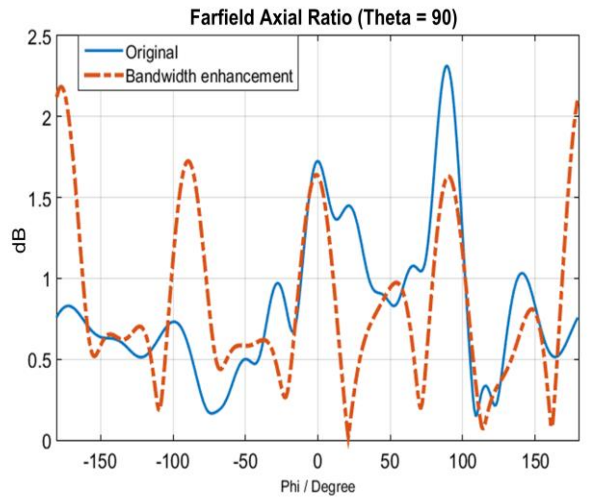


Figure 14. The axial ratio patterns of the antennas of first and second versions in azimuth plane at 11.75 GHz.

Although the azimuth plane gain variation and axial ratio performances of first version is slightly lower than the second version at the center frequency of the design (11.75 GHz), the second version is superior to first version at the higher frequencies due to the advantage of having wideband characteristics. For instance, the gain variation and axial ratio performances of both versions are compared in Figure 15. According to the results in Figure 15, both versions have similar axial ratio performances such that the values are below 2.4 dB at 12.25 GHz. On the other hand, the gain variation of narrowband design, which is about 10 dBi at 12.25 GHz, is undesirably high. The gain variation of wideband version is just 3 dBi at the azimuth plane in the same frequency, which is more convenient for the applications with omnidirectional property.



(a)



(b)

Figure 15. (a) Rectangular radiation patterns and (b) axial ratio of the antennas of first and second versions in azimuth plane at 12.25 GHz.

5. Conclusions

In this study, two versions of circularly polarized omnidirectional antennas, which can be used in satellite communication systems of telemetry and telecommand antennas, are designed and demonstrated. The bandwidth of the narrow band antenna is enhanced with the modifications of dimensions of the slotted antenna array elements. The usage of nonidentical slotted antenna array elements degrades the farfield performance as compared to narrow band antenna design; but, these effects can be acceptable when considering general antenna standards. There is a tradeoff between farfield performance of the antennas and bandwidth of the antennas. The frequency bandwidth of the narrow band antenna is increased from 272 MHz to 680 MHz for telemetry example. However, the second version (enhanced version) also makes undesired increase about 1 dB in both gain variation and axial ratio values; but, the corresponding results are still sufficient. Wideband antenna design may be preferred in wideband applications where narrow band version can be used in the applications with more challenging specifications for gain variation and axial ratio.

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