A wideband quadruple-ridged horn antenna for the multifeed S-band receiver of the Sardinia Radio Telescope

A feed horn for the multifeed S-band receiver of the Sardinia Radio Telescope has been designed. The antenna consists of a truncated circular waveguide with four ridges of variable height inside. The horn antenna has been designed and tested by using Ansys HFSS and, then, the multifeed system has been coupled with the Sardinia Radio Telescope by using GRASP by TICRA. The return loss of the feed horn is larger than 20 dB over a 60% bandwidth (between 2.3 GHz and 4.3 GHz), and the edge taper and the cross-polarization level of the multifeed system meet the specifications of the Sardinia Radio Telescope S-band receiver.

Keywords: feed horn, quadruple-ridged waveguide, Sardinia radio telescope

1. Introduction

The performance of radio telescopes strongly depends on the illumination of its mirror, which can be realized using a suitable feed placed in ones of the foci of the telescope. Then, the feed design, which should provide the required specifications for the application at hand, is an important step to perform effective radio astronomy observations. In particular, the feed system of a radio telescope, which is typically realized using waveguide horns [1], must illuminate the reflector surface with a low cross-polarization, in order to discriminate the different polarizations of the sources, and must provide a wideband frequency behavior, according to required radio astronomy applications.

The aim of this work is to design a waveguide feed for the S-band multifeed receiver of the Sardinia Radio Telescope (SRT) [2], located in the primary focus of the antenna.

The receiver will cover the frequency range between 2.3 GHz and 4.3 GHz (with a relative bandwidth of about 60%), and has been selected to allow different radio astronomy observations, such as: pulsar observations (survey and monitoring) in the galactic center region; evaluation of the variation of the pulsar dispersion; simultaneous observations of pulsars within the Large European Array for Pulsars (LEAP) for gravitational wave detection; mapping and characterization of the radio spectra of galactic supernova remnants and/or study of the radio polarization of a sample of halos in nearby galactic clusters.

Since the S-band receiver is intended to be mounted in the primary focus of SRT, a suitable edge taper must be provided by the feed to achieve the optimal illumination of the 64-meter primary parabolic surface of SRT. Moreover, in our case, the single feed is a part of a multifeed configuration and, therefore, the feed design must also take into account the limited room available in the focal cabin of SRT, and the load constraints of the primary focus positioner (see Fig. 1 of [2]). In other words, our target is to house as much feeds as possible in a focal plane array in order to maximize the field of view of the radio telescope. As a consequence, each single feed horn of the “multifeed array” must be compact, light, and with a reduced radiating aperture.

Waveguide horns for radio astronomy applications are typically realized using a rectangular or a circular waveguide, which flares into a wider open-end radiating termination, using different configurations and shapes [3]. However, standard waveguide horns are usually too directional to effectively illuminate such a large reflector as the 64-meter primary reflector of SRT. Moreover, their operating frequency band is of the order of 40-50%, which is not enough to comply with the specifications of the S-band receiver of SRT. Finally, the radiating aperture of a standard waveguide horn could be too large to be employed in a multi-feed system, especially in our case, wherein space and weight constraints are critical.

In order to meet the design specification of the feed system, both on the bandwidth and on the required edge taper, keeping a compact and light realization, and aiming to minimize the waveguide horn transverse section, we have selected a ridged circular waveguide configuration [4-6]. This solution allows us to increase the useful bandwidth, since it lowers the cutoff frequency of the circular waveguide fundamental mode.

Different configuration of quadruple-ridged horn antennas for radio astronomy applications are available in the literature, as proposed in [7-11]. However, in all of these works the physical dimension of the horn radiating aperture is too large for application in the multifeed system of SRT. Moreover, those solutions are found not suitable to illuminate the primary reflector of SRT, which has an F/D of 0.33.

In this paper, we exploit the advantages of the quadruple-ridged circular waveguide in terms of a larger bandwidth, thus achieving a very good input match over the desired frequency band. Then, to realize a relatively small radiating aperture we use a suitable taper of the ridges inside the circular waveguide [12], but keeping always the same external transverse dimension of the feed in the longitudinal direction, i.e. without flaring into a wider open-end termination. This allows the required multifeed implementation, and also an effective illumination of the SRT primary reflector.

The design and optimization of the proposed waveguide feed horn have been performed using the FEM commercial software Ansys HFSS. Simulated results show an operating bandwidth of 60%, with a reflection coefficient below -20 dB, an edge taper illumination between 8.3 dB and 19.4 dB at ±74°, with a good cross-polarization. Then, the performance of the designed antenna has been validated by embedding it in the full SRT model realized with the 3D software Grasp by Ticra. This simulation tool is specifically tailored for the analysis of large radio telescopes, providing a very accurate modelling, and its results are, therefore, always in very good agreement with experiment [13].

2. Design and optimization of the feed

The geometry of the proposed feed is shown in Figure 1. It essentially consists of a truncated circular waveguide with four ridges of variable height inside. In the design and optimization of this configuration, we can identify three parts: a circular waveguide of diameter D_I; four ridges with a sinusoidal profile; the open-end radiating termination. Each one of these parts must be accurately designed to comply with the required specifications, which are reported in Table 1.

The circular waveguide diameter D_I has been selected equal to 86 mm. This value is dictated by the architecture of the circular Ortho Mode Transducer, which is realized using the same quadruple-ridged configuration [2], and will be connected to the input port of the feed. The waveguide diameter, together with the initial dimensions of the ridges (i.e. H_{RI}, W_R in Figure 1d), determines the cut-off frequency of the fundamental mode of the ridged circular waveguide, which, in our case, is equal to 0.9 GHz, i.e. well below the starting frequency of the receiver operating bandwidth.

The choice of the profile of the ridges, which can be observed in Figure 1b, is a key point in the antenna design, since it must be suitably selected to match the 50 Ω input impedance of the ridged waveguide to the free space impedance. Different profile options are available to the feed-horn designer, and have been investigated in [12]. For our application, we have found that the best results are achieved using the sinusoidal profile (see Figure 1), which is described by the following equation:

$$a(z) = a_i + (a_0 - a_i)\left[(1-A)\frac{z}{L} + A\sin^p\left(\frac{\pi z}{2L}\right)\right] \qquad (1)$$

wherein a_i e a_o are, respectively, the initial height of the ridges (i.e. H_{RI}, at the input port of the feed), and the height of the ridges at the end of the sinusoidal profile (H_{RO} in Figure 1c); L is the length of the ridges along the sinusoidal tapering and, in our case, is equal to 270 mm; the parameter A varies in the range [0, 1] and weighs the profile linearity; $p \in [0, \infty]$ is the exponent of the sine. The optimization of the latter parameter is very important since it strongly influences the side-lobe level (SLL) and, therefore, the illumination of the reflector. In our case, we have selected $p = 6$, which provides the required SLL.

The final stretch of the feed, including a ridged circular waveguide with constant section, of length L_F, and a radiating aperture with an indentation of dimensions W_{F1}, W_{F2}, H_{F1}, H_{F2} (see Figure 1c) has been optimized for the best input match over the operating bandwidth.

As apparent from the profile of the ridges, shown in Figure 1b, another indentation of dimensions H_I, W_I (see Figure 1b) has been realized at the distance L_I form the input port of the feed. This parameter has been used as a further parameter in order to improve the input match.

The optimization procedure on the parameters L_F, H_{F1}, H_{F2}, W_{F1}, W_{F2}, H_I, W_I, and L_I has been performed using Ansys HFSS and the final values are reported in Table 2.

In Figure 2 we show the frequency response of the feed (S_{11}) for different values of the length L_I, in Figure 3 the frequency response for different values of the length L_F and, in Figure 4, the frequency response for different values of the height H_{F1}.

3. Results

The design so far has considered an isolated feed horn, but the real implementation involves an array of seven elements in a hexagonal grid [5]. The choice of the spatial configuration in this hexagonal grid and the number of feeds on a focal plane array (FPA) have been selected to maximize the Field of View of the antenna, keeping in mind the available room in focal cabin of SRT and the load limit of the primary focus positioner (PFP). The minimum distance between the centers of the feeds, which maximize the aperture efficiency of the antenna and produces the better mapping of an extended radio astronomical source, is equal to 100 *mm* [2]. The design of the radiating aperture of single feed described above takes into account the limited space available. Moreover, in order to minimize the mutual coupling effect between the feeds, we decided to fill the space between feeds with an absorbing material (Eccosorb MF-124). In Figure 5 the layout of multifeed with enclosure is shown.

In this section, simulation results of the proposed antenna are presented. The reflection coefficient of the isolated feed is below -20 dB over a 60% bandwidth (Figure 6). In order to evaluate the mutual coupling effect between the feeds in the multifeed configuration, in Figure 6 we also show the simulated reflection coefficient of the central feed when included in the multifeed array, and, also in this case, the reflection coefficient remains below -20 dB, thus complying with the feed design specification on the return loss (see Table 1).

Figures 7-9 show the normalized radiation pattern in the $\phi=0°$, $\phi=45°$, and $\phi=90°$ planes at the frequencies 2.3 GHz, 3.3 GHz, and 4.3 GHz. Variations between the patterns can be observed at these frequencies. The radiation patterns of only one polarization are plotted for brevity. However, the performance of the other polarization is virtually the same.

As can be seen from Figure 8, the initial request of an edge illumination of -13 dB at 74° at 3.3 GHz (see Table 1) was basically met, whereas the edge illumination at 2.3 GHz and 4.3 GHz is, respectively, -9 dB and -19 dB. The radiation pattern at the central frequency, 3.3 GHz is optimal; the pattern at 2.3 GHz is quite good, and at 4.3 GHz the edge taper can be considered still acceptable [2].

The electromagnetic coupling between the Sardinia Radio Telescope and the multifeed horn system has then been simulated in order to estimate the antenna gain and the cross-polarization component. The complete system has been modelled using the 3D analysis software GRASP 9 by TICRA. In the GRASP model of SRT we have taken into account the blocking effects of the subreflector, with an 8 m diameter hole centered in the main reflector, and the quadrupod structure (struts). In Figures 10-12 we show the radiation pattern of the SRT illuminated by the central feed of the multifeed array, at 2.3 GHz, at 3.3 GHz, and at 4.3 GHz. The antenna gain is between 61 dBi at 2.3 GHz and 66 dBi at 4.3 GHz. The cross polarization level is very good (below -30 dB) at 2.3 GHz and 3.3 GHz, whereas it is quite higher (-20 dB), but still acceptable, at 4.3 GHz, caused by the particular design of radiating aperture.

4. Conclusion

A wideband quadruple-ridged horn antenna for the multifeed S-band receiver of the Sardinia Radio Telescope has been presented. The antenna consists of a truncated circular waveguide with four ridges of variable height inside. The design of the feed takes into account the constraints of the multifeed configuration. The horn performance is very good, especially in terms of return loss, which is larger than 20 dB over the operating bandwidth, and meets the general requirements of the Sardinia Radio Telescope S-band receiver.

References

[1] Balanis C. A.: ‘Antenna Theory: Analysis and Design’ (Wiley, NJ, 2005).

[2] Valente G., Serra G., Gaudiomonte F., Ladu A. et al.: ‘A MultiFeed S-Band Cryogenic Receiver for the Sardinia Radio Telescope Primary Focus’. In: Proceedings of SPIE, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII, Vol. 9153, 2014.

[3] Olver A. D., Clarricoats P. J., Kishk A. A., Shafai L.: ‘Microwave Horns and Feeds’ (IET, London, 1994).

[4] Walton K. L., Sundberg V. C.: ‘Broadband ridged horn design’, Microwave Journal, 1964, pp. 96-101.

[5] Sun W., Balanis C. A.: ‘Analysis and design of quadruple-ridged waveguides’, IEEE Trans. Microw. Theory Tech., 1994, 42, (12), pp. 2201-2207.

[6] Chen M. H., Tsandoulas G. N., Willwerth F. G.: ‘Modal characteristics of quadruple-ridged circular and square waveguides’, IEEE Trans. Microw. Theory Tech., 1974, 22, (8), pp. 801–804.
[7] Akgiray A., Imbriale W. A., Beaudoin C.: ‘Circular Quadruple-Ridged Flared Horn Achieving Near-Constant Beamwidth over Multioctave Bandwidth: Design and Measurements’, IEEE Trans. Antennas Propag., 2013, 61, (3), pp. 1099-1108.
[8] O. B. Jacobs, J.W. Odendaal and J. Joubert, “Quad Ridge Horn Antenna with Elliptically Shaped Sidewalls”, IEEE Trans. Antennas Propag., 2013, 61, (6), pp. 2948-2955.
[9] Dunning A., Bowen M., Bourne M., Hayman D., Smith S.L.: ‘An Ultra-Wideband Dielectrically Loaded Quad-Ridged Feed Horn for Radio Astronomy’. In: Proceedings of the IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications. Turin, September 2015, pp. 787-790.
[10] Giacomini A., Potenza A., Morbidini R., Foged L.: ‘Quad-ridge Dual Polarized Antenna for Use in the 2-32GHz Band’. In: Proceedings of the 6th European Conference on Antennas and Propagation (EUCAP). Prague, March 2012, pp. 769-772.
[11] Wenliang Z., Jinghui Q., Xianqing S.: ‘Quad-ridge Dual Polarized Horn Antenna Design and Optimization’. In: Proceedings of the 3rd Asia-Pacific Conference on Antennas and Propagation, Harbin, July 2014, pp. 643-646.
[12] C. Granet: ‘Profile options for feed horn design’. In: Proceedings of the Asia-Pacific Microwave Conference. Sydney, Australia, December 2000, pp. 1448-1451.
[13] Focardi P.: ‘Large/complex antenna performance validation for spaceborne radar/radiometeric instruments’. In: Proceedings of the IEEE Antennas and Propagation Society International Symposium. Orlando, FL, July 2013, pp. 2175-2176.

Operating bandwidth	1.3 GHz – 4.3 GHz
Return Loss	> 20 dB
Edge Taper @ 74 degrees (3.3 GHz)	-13 dB
Cross-polarization	< -20 dB
Feed diameter	< 91 mm

Table 1. Feed design specifications.

L_F	H_{F1}	H_{F2}	W_{F1}	W_{F2}	L_I	H_I	W_I
70 mm	76 mm	68 mm	5 mm	5 mm	180 mm	20 mm	6 mm

Table 2. Optimized parameters of geometry feed.

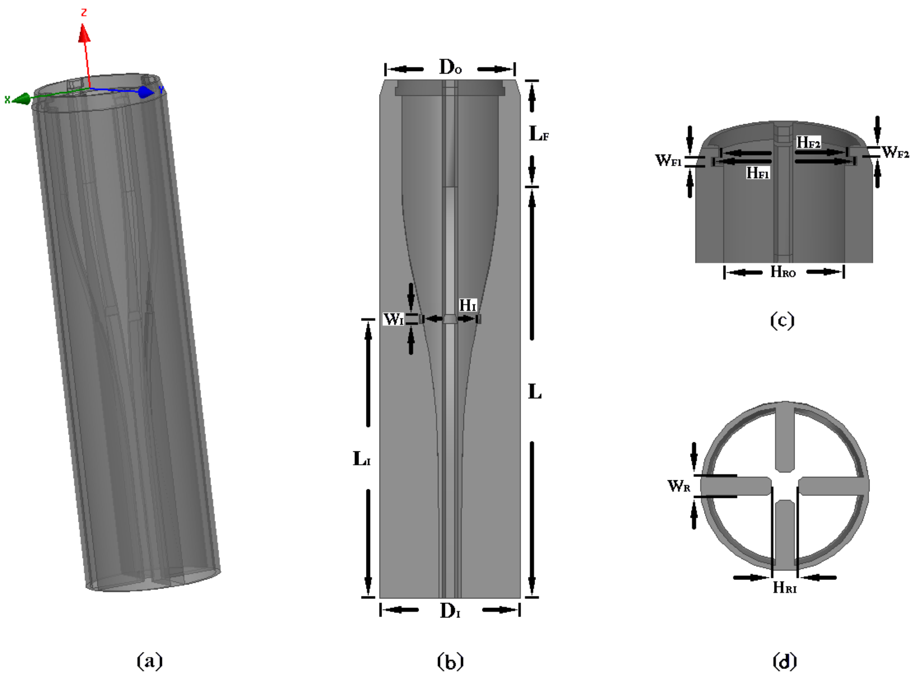

Figure 1. Geometry of the proposed quadruple-ridge horn antenna: (a) 3D view; (b) sectional view; (c) detailed view of radiating aperture; (d) view from the bottom looking up.

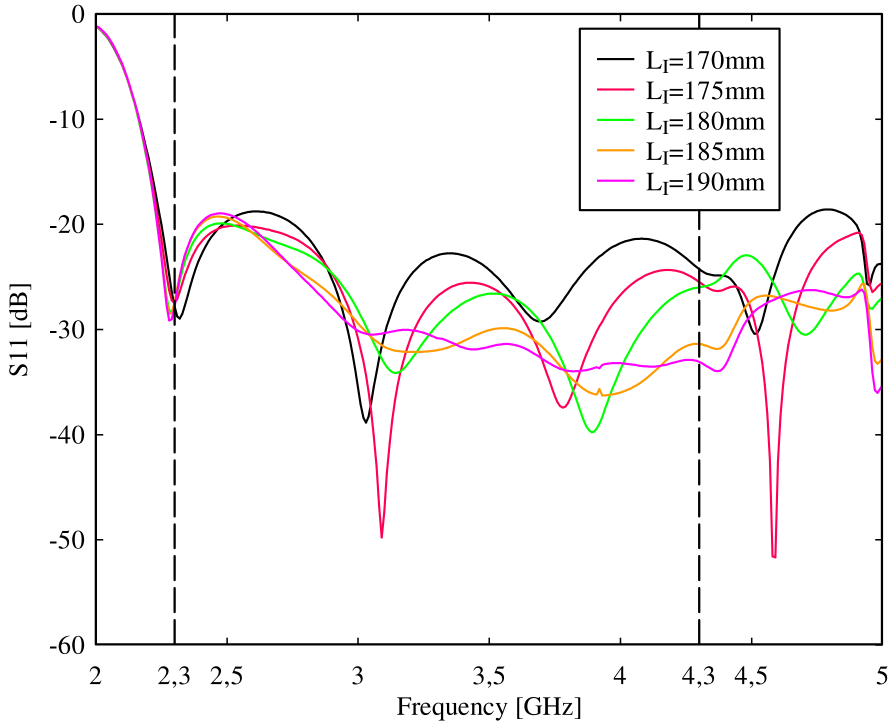

Figure 2. Frequency response for different values of the length L_I.

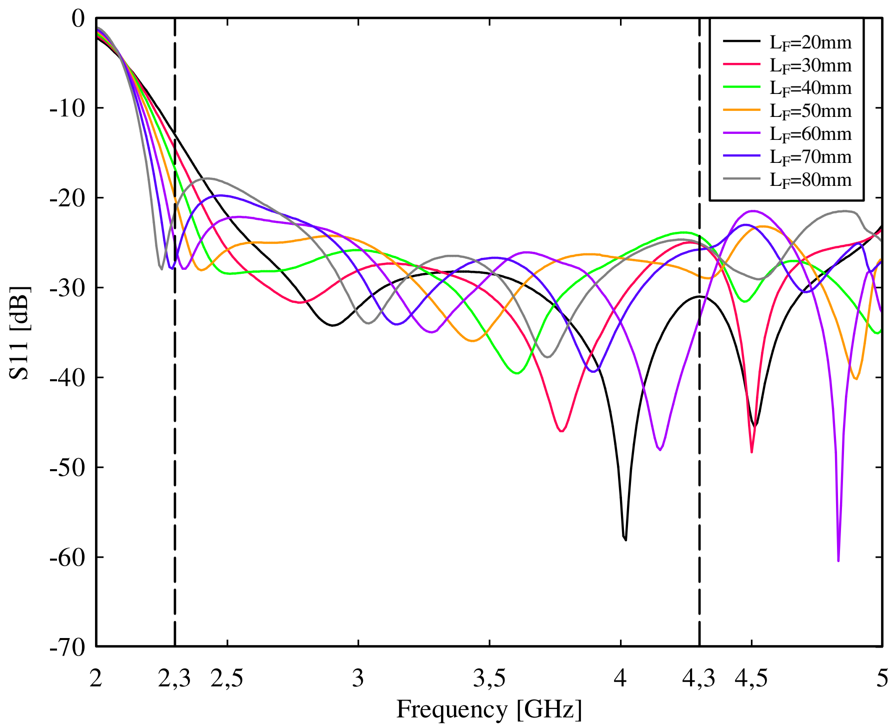

Figure 3. Frequency response for different values of the length L_F.

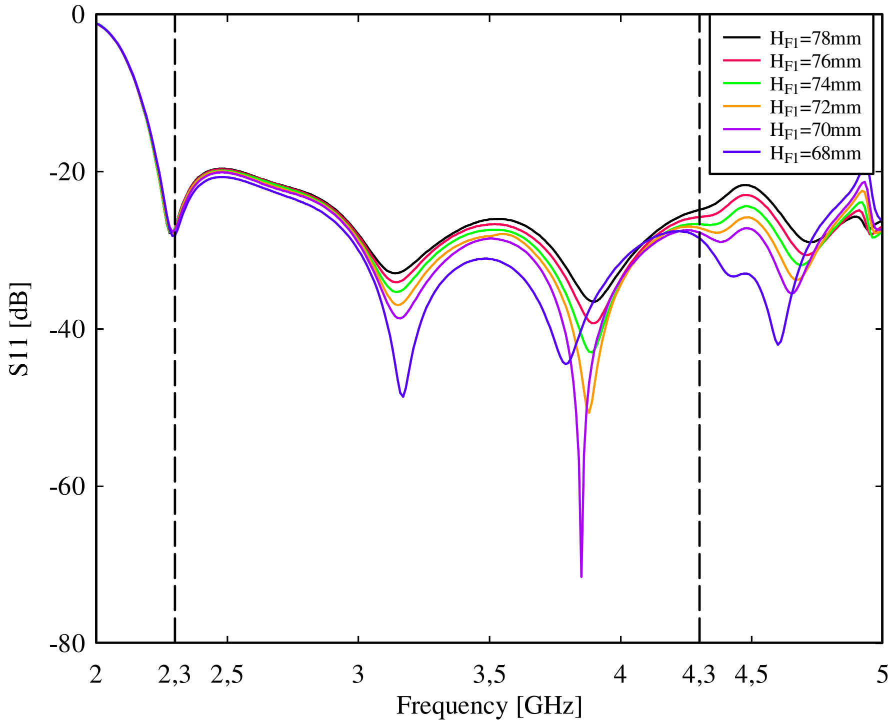

Figure 4. Frequency response for different values of the length H_{F1}.

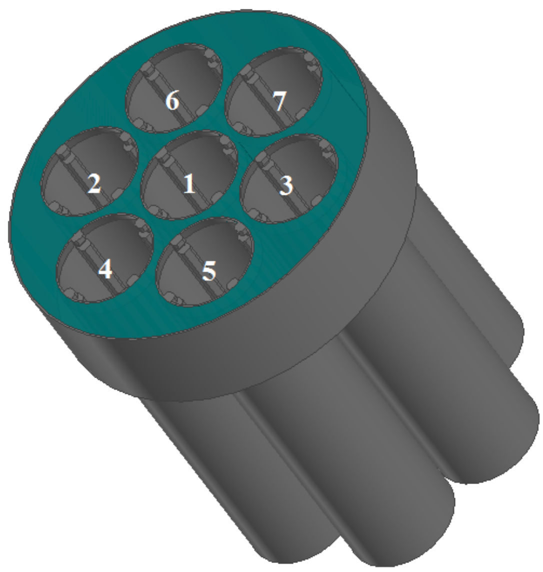

Figure 5. Multifeed layout.

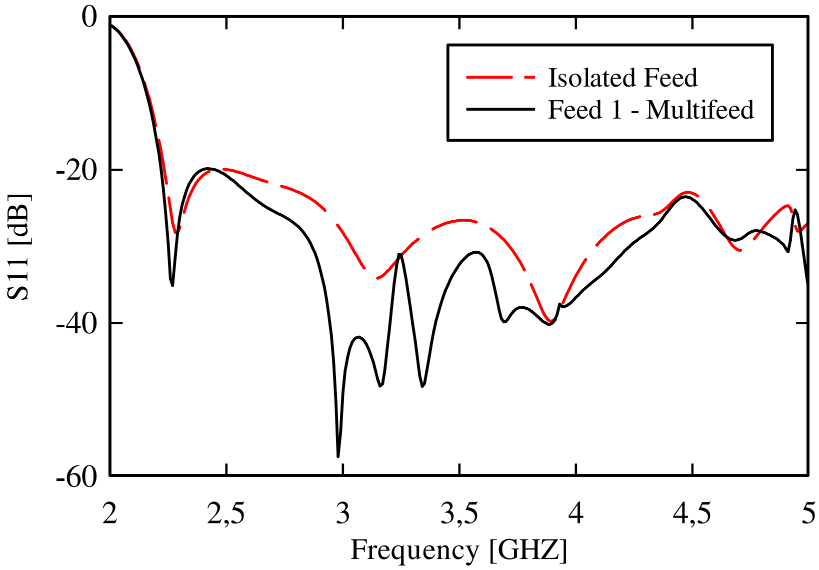

Figure 6. Simulated reflection coefficient of the isolated feed and of the central element of the multifeed configuration.

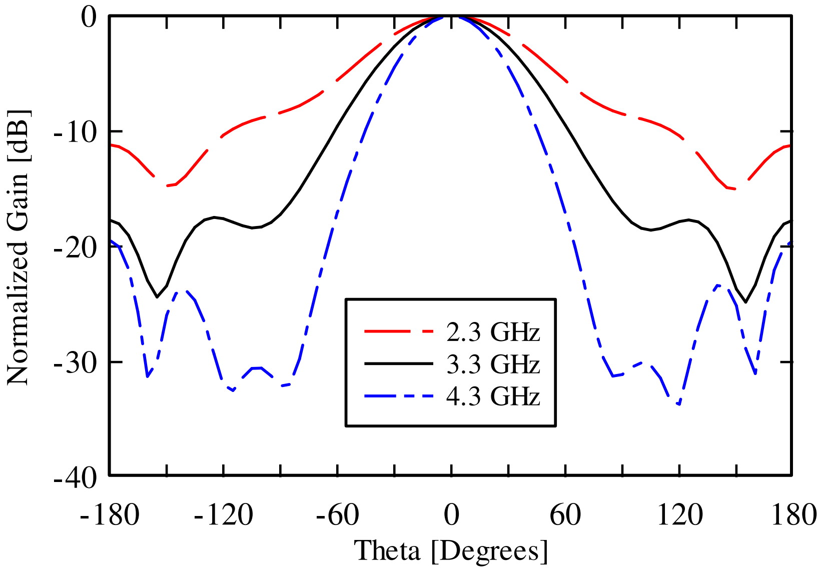

Figure 7. Normalized radiation patterns of the isolated feed at 2.3 GHz, 3.3GHz and 4.3 GHz in the $\phi = 0°$ plane.

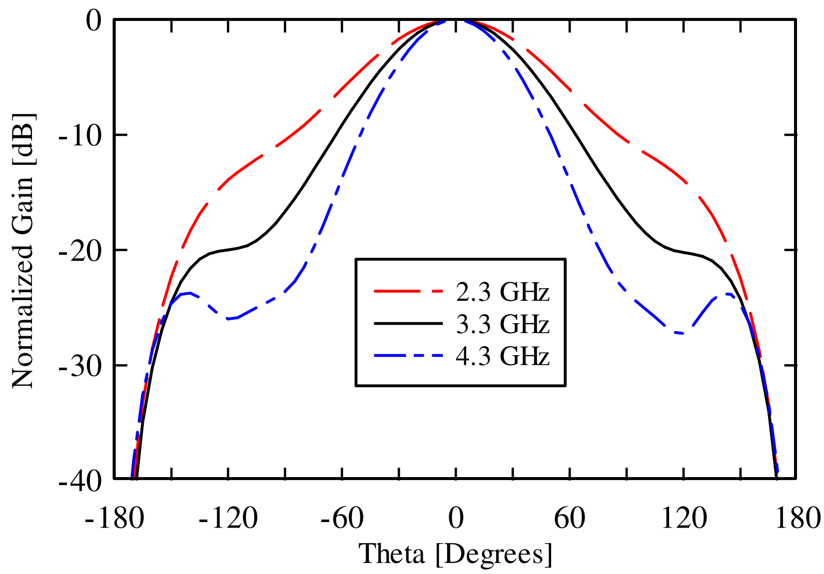

Figure 8. Normalized radiation patterns of the isolated feed at 2.3 GHz, 3.3GHz and 4.3 GHz in the $\phi = 45°$ plane.

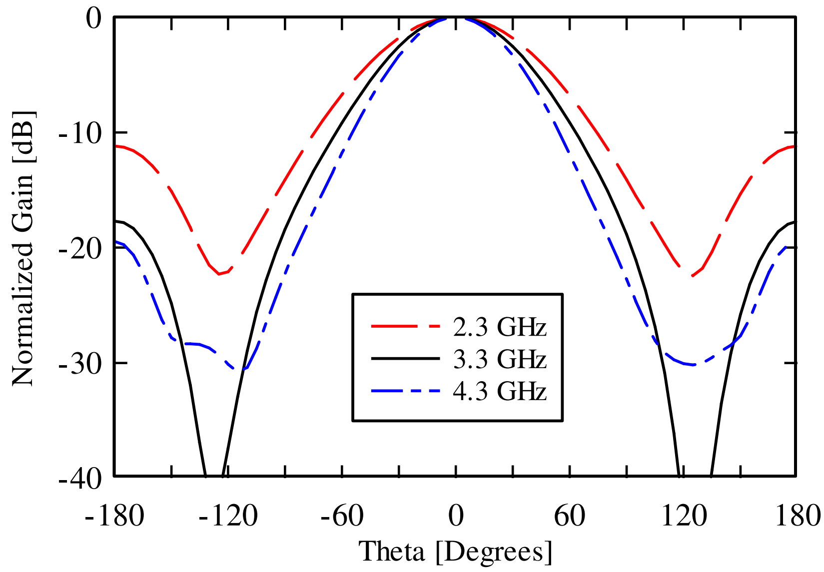

Figure 9. Normalized radiation patterns of the isolated feed at 2.3 GHz, 3.3GHz and 4.3 GHz in the $\phi = 90°$ plane.

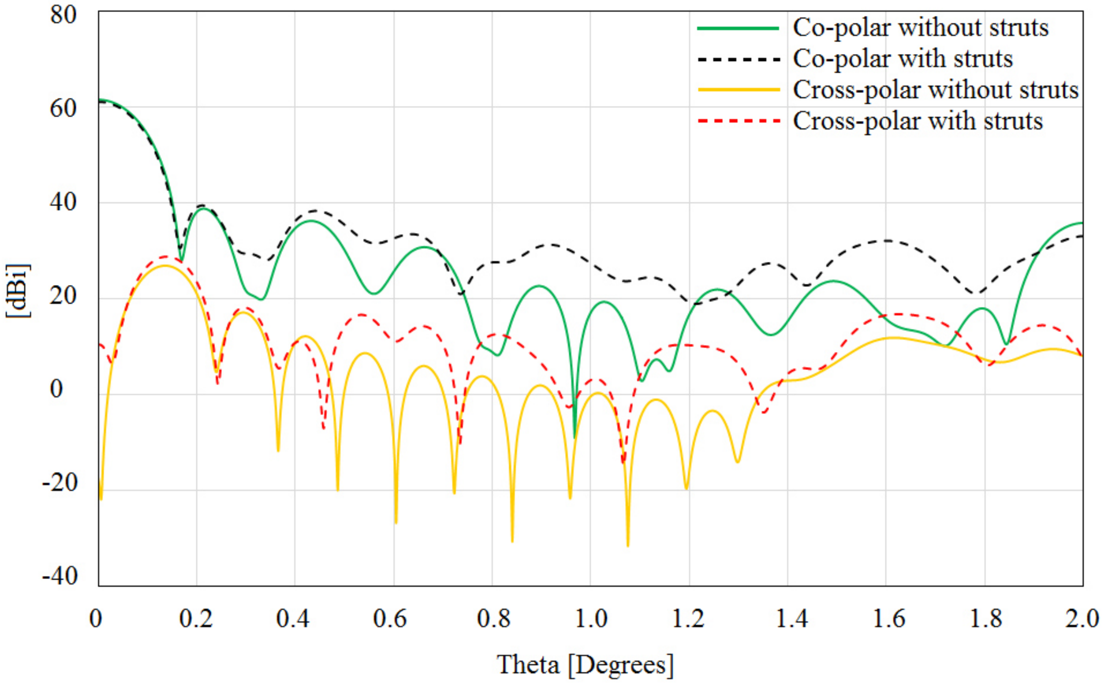

Figure 10. Radiation pattern of the SRT with the multifeed system at 2.3 GHz.

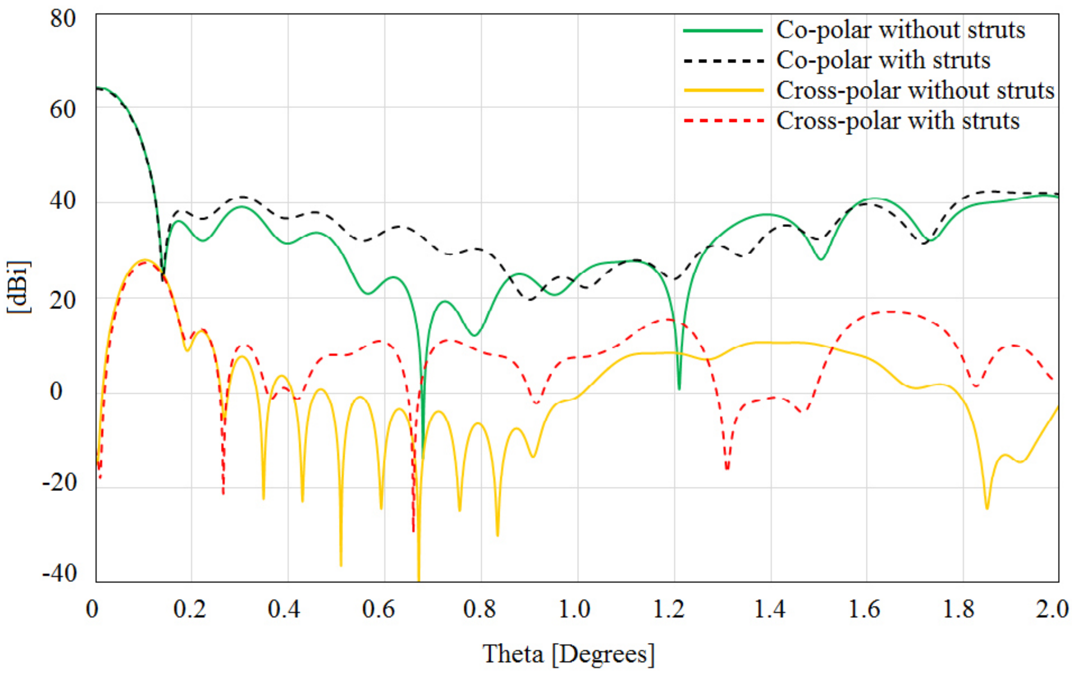

Figure 11. Radiation pattern of the SRT with the multifeed system at 3.3 GHz.

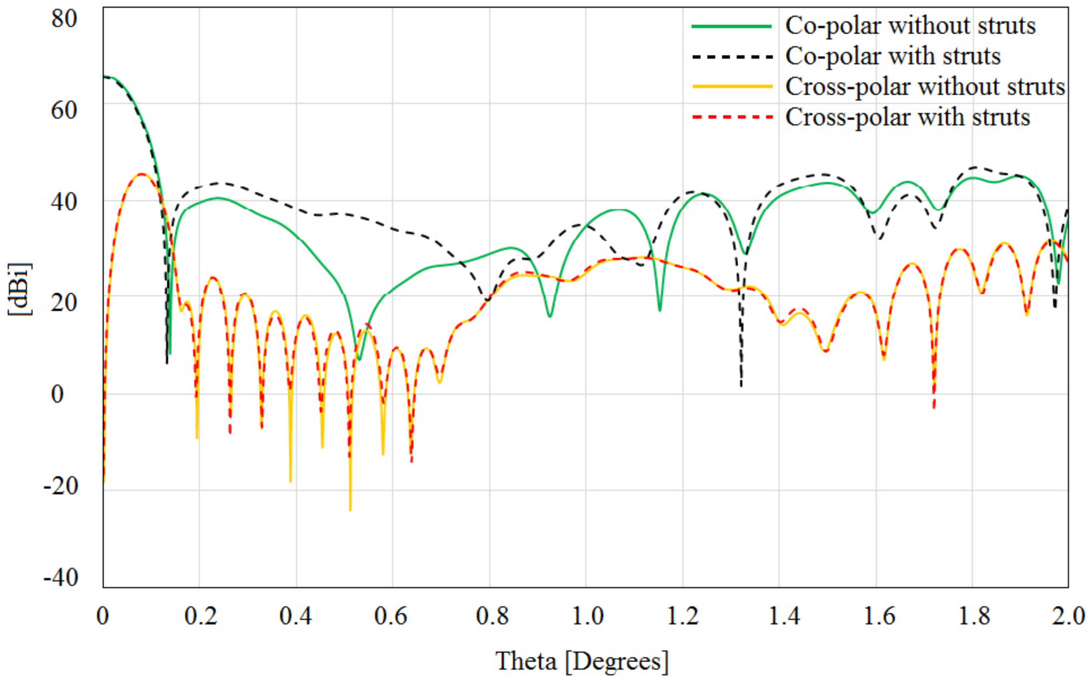

Figure 12. Radiation pattern of the SRT with the multifeed system at 4.3 GHz.